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Journal of Sedimentary Petrology

A Publication of the Society of Economic Paleontologists and Mineralogists
a Division of
The American Association of Petroleum Geologists

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Journal of Sedimentary Petrology

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Articles submitted for publication to the *Journal of Sedimentary Petrology* should have a prefatory abstract and sufficient postage should be sent by the author to pay the return of the manuscript as it has been found that many articles require more or less revision before publication.

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Among papers to appear in forthcoming issues of the *Journal* are the following:

Measures for describing the size distribution of sediments. By Douglas L. Inman.

Mineralogy of some Australian desert soils. By Dorothy Carroll.

Fathogram indications of bottom materials in Lake Michigan. By J. L. Hough.

Clay and other non-carbonate minerals in some limestones. By Carl Robbins and W. D. Keller.

Trails and rocks observed on a playa in Death Valley National Monument, California. By Louis G. Kirk.

Wind-blown rocks and trails on Little Bonnie Claire Playa, Nye County, Nevada. By Thomas Clements.

Recent history of a sand spit at San Nicolas Island, California. By Robert M. Norris.

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FIGS. 1–3, JUNE, 1952

WAS DECAY IMPORTANT IN ORIGIN OF COAL?[1]

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ABSTRACT

Microbiotic conditions that existed in ancient peat deposits prior to their coalification were probably highly varied. Some of the probable variations are discussed with reference to common plant products and different agencies of decay. Differences in sulfur content may reflect greater anaerobic decay in Paleozoic than in younger coals, and the prevalent remains of saprophytic fungi in post-Jurassic coals suggests that, in these, aerobic decay was of proportionately greater importance. Plant material contributing to Paleozoic coal was, in general, less subject to mechanical degradation than is apparent in the younger coals in which the peat was affected by saprophytic fungi.

INTRODUCTION

The origin of petroleum is replete with many unsolved problems, but in a general fashion the manner of coal origin is perfectly clear. Thus it is possible to say that decay took place and *was* important in the origin of many types of coal. There are, however, several modes of decay, and we can progress a little way now in suggesting which of these was of greater or lesser importance in the origin of coal types, or of coal deposits of different ages. Of course, reconstruction of the microbiology of peat now converted into coal cannot be very exact and cannot be expressed in terms entirely coordinate with those used in evaluating modern microbiologic environments. For the present, and possibly for a considerable time to come, we shall have to phrase our coal microbiologic interpretations cautiously.

METHODS OF STUDY

The quantitative methods that are most useful in interpreting coal microbiology, and for many other purposes of coal geology, were initiated by Thiessen (1931) about 20 years ago at the U.S. Bureau of Mines Coal Constitution Laboratory in Pittsburgh. A point to be emphasized is that the quantitative information, essential to any relative evaluation of processes in coal formation, was not evolved until Dr. Thiessen had already spent at that time more than 20 years in the study of coal. Other quantitative methods that differ in important particulars have been devised since 1931, but most of these methods do not permit the same refinements of observation that are possible by Thiessen's method for estimating classes of components observed in coal thin sections, *based on a standard procedure*. A recent evaluation of the Thiessen procedure has been presented by Parks and O'Donnell (1949).

Although more coal beds have been investigated by Thiessen's method than by any other, the coal fields in the United States alone are relatively enormous and have not been adequately mapped or sampled. This lack of fundamental data concerns us in discussion of a general topic such as the role of organic decay. The available data are derived chiefly from coal that is mined commercially, and these datum points are not sufficiently well distributed to serve our present purpose to the greatest advantage. Nevertheless, certain features stand out, and a relative and semi-quantitative estimate of some of the microbiologic conditions can be ventured.

[1] Published by permission of the Director, U. S. Geological Survey.

Paper presented at a joint meeting of the Paleobotanical and Microbiological sections of the Botanical Society of America, December 28, 1949, as a part of the symposium on "Microbiology in Relation to the Geologic Accumulation of Organic Complexes."

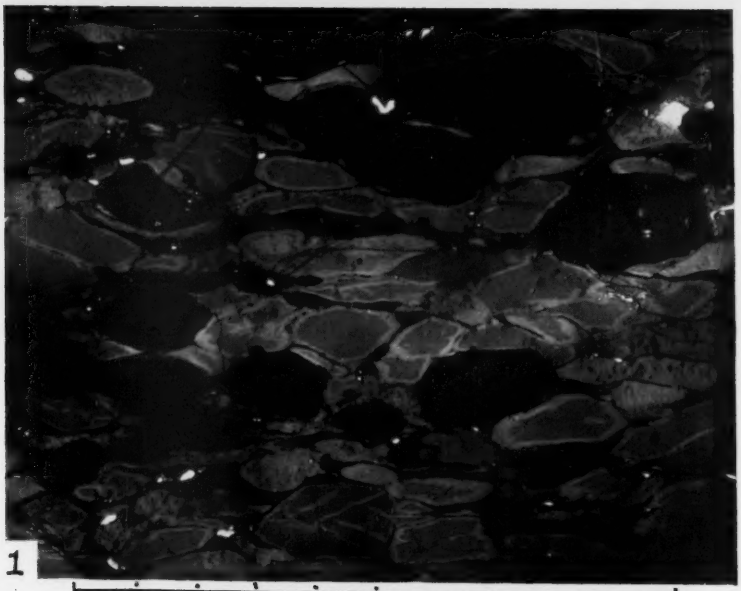
CONDITIONS IN ANCIENT PEAT SWAMPS

Coal was formed by the consolidation of peat. The Paleozoic peat swamps contrasted in several ways with any comparable modern deposits that I know of. The morphologic organization of the dominating Paleozoic plants was generally different from that of plants which contribute to any modern peat deposits. The important Paleozoic coal-forming plant types, for example, were principally arborescent lycopsids, psaronii, and semi-succulent pteridosperms. In my opinion the role of emphatically exogenous plants, such as the cordaitaleans, was not often a prominent one in formation of our Paleozoic coal. This difference seems to be largely responsible for the distinct lithologic contrast between the more or less even-banded coals of Paleozoic age, and those of Cretaceous and Tertiary age, which tend to include less numerous but thicker and more prominently lenticular bands of vitrain or its equivalent. The younger coals must have been derived from peat resembling the types found in paralic and estuarine deposits of the present day.

Although these differences are important, the microbial environment of the Paleozoic and later coals may be compared because, as far as we know, the initial organic compounds that formed ancient plants were similar to those now synthesized by recent ones. Nevertheless, important microbiotic differences probably also existed. Before discussing these let us first visualize the general process of peat formation where this is dominated by arborescent vegetation. The peat deposits that became transformed into beds of commercial coals that we know best, and, in fact, the great majority of all coal deposits known, were dominated by an arborescent plant assemblage. The mosses and mosslike plants, which we are apt to think of when peat is mentioned today, evidently were not very important in forming coal.

Every year the peat swamp flora produces an additional increment of organic matter through normal growth processes. Every year plants die, and a considerable additional volume of litter is shed from living individuals to accumulate on the upper surface. The litter and exposed dead trunks are a fertile substrate for aerobic microorganisms and xylophagous insects as long as they remain above the water table. In peat swamp environments, however, original small fragments may soon settle and lodge in an anaerobic environment, where they are more protected from decay. The largest dead trunks, when they are overthrown, tend to sink more deeply into the litter because of their weight, and they are likely to arrive in the *anaerobic* peat environment sooner on that account. The subterranean parts of plants growing on the peat swamp may never be subject to aerobic saprophytic attack, because they grew and died so near the saturation level or below it. Examples of fossil parasitic or symbiotic fungi infecting subterranean organs have been reported in several instances (Andrews and Lenz, 1943), and the water-table relationship just mentioned may be chiefly responsible for these best-preserved examples of fungi from the more ancient coal deposits.

Thus the smallest fragments that can lodge at the bottom of the litter, the largest fragments that can on occasion crush their way to the zone of saturation, and the subterranean plant organs that are already adjacent to the water table, all have greater opportunity to escape full exposure to decay. It is the litter fragments of intermediate size—too coarse or cumbersome to lodge deeply or to be transported easily to an anaerobic environment and not heavy enough to sink quickly of their own weight—that are likely to be *most* decayed before incorporation into the coal swamp peat. Once the organic material is permanently submersed below the water table its compaction ensues, and its stratification and relative location in the deposit seems permanently fixed.



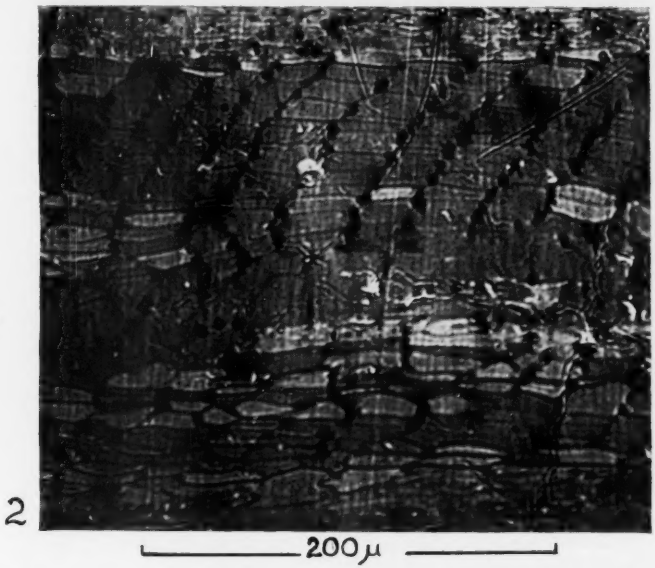


FIG. 1. Resinous bodies, in various modes of preservation, concentrated as a result of selective decay. Scale of magnification indicated. Witbank coal, Union of South Africa.

FIG. 2. Coalified periderm (anthraxylon) showing cells of at least two types, wall structure well preserved, lumens collapsed. Scale of magnification indicated. D. N. C. coal, Union of South Africa.

A great variation must have existed in the microbiotic environments of the different types of material composing any peat deposit, regardless of the class of plants that contributed to it. Any thorough microscopical study of coal will convince the observer that enormous differences in the preservation of plant parts in the same bed of coal is the *rule—not the exception*. It is also proper to emphasize the influences of the subaqueous environment in inhibiting the growth of aerobic and influencing anaerobic decay-producing microorganisms. Purely chemical decay, in the total absence of living organisms, also can take place in the subaqueous environment (Varossieau, 1949).

Doubtless biotic and chemical alteration is retarded in proportion to subsequent compaction and reduction of pore space, and to the extent to which "tightening" of the organic deposit restricts molecular interchange and diffusion. The diagenetic stage of coal formation, about which we are relatively ignorant, includes gross dehydration of the peat and its consolidation. At some point, anaerobic as well as aerobic decay is permanently retarded. Unfortunately, the organisms directly responsible for anaerobic decay can not be positively identified in coal, and we must evaluate their importance by indirect methods. Considerable evidence, ably presented in other papers in this symposium, shows the general importance of anaerobic decay on organic substances under differing environmental conditions (see Barghoorn, Zo Bell, among others). However, the effects of anaerobic decay are not usually given much prominence in discussion of coal formation, probably because mechanical attrition and the resulting microfragmentation, which is also to be considered as part of the process of decay, may be largely a result of aerobic degradation.

PRESERVATION OF PLANT PRODUCTS

It is common in theoretical discussion of coal formation to speak of the differences in resistance of various plant products to decay, commencing with protoplasmic materials and progressing through hemi-cellulose, cellulose, lignin, to certain waxes and resinous substances.

I must confess that this ideal sequence is rarely observed by the coal microscopist. However, figure 1, a photomicrograph taken by transmitted light from a thin section of South African coal, illustrates a most extreme example of selective decay. All the bodies shown in this illustration are obviously of similar secretory derivation, concentrated by decay of enveloping plant tissues, yet these originally uniform secretory bodies present extreme contrasts in mode of preservation. Most of them are vitrinized, red translucent with an orange marginal halo in the original thin section, but some are brownish translucent and others are essentially opaque. The opaque secretions have held to their original oval form, and evidently are fusinized; the vitrinized secretions have become moulded against one another and against the fusinized secretions. These modes of preservation have been discussed in greater detail elsewhere (Schopf, 1948). I do not think these modes of preservation have direct relationship to processes of decay, as ordinarily considered; however, they influence the appearance of microscopic structures in coal to such an extent that the results of decay may be difficult to distinguish clearly from differences relating to mode of preservation. Figure 2, also from South African coal, shows normal vitrinized preservation of periderm (classified as anthraxylon in Thiessen's system) with excellent cellular detail. The complexity of the problem becomes more evident when one finds such differences in degree of decay, as well as concomitant differences in modes of preservation, within different layers of the same coal bed. Transitions frequently are abrupt and complete graduations, easy to interpret, are often wanting.

Similar differences, more or less, can be found in most coal deposits, of both

Paleozoic and younger age. The author (Schopf, 1947) previously has presented illustrations of coal of Eocene age from the Coos Bay coal featuring the varied preservation of woody tissues and remains of saprophytic fungi. In such coal we also have excellent material to check microscopically on pertinence of chemical theories regarding exclusion of cellulose. Cell walls of wood rays, in particular, are known to be cellulosic. In many instances the wood rays are beautifully outlined in specimens of coalified wood and, although these cellulosic walls have been altered, it is clear that substance *derived from cellulose* is still present. The same reasoning applies to walls of leaf mesophyll and other parenchymatous (cellulosic walled) tissues that occasionally are seen coalified in good microscopic detail. Probably similar tissues contribute more to coal than can be clearly demonstrated because distortion could easily obscure clear botanical definition of the structure.

There is no uniformity in the plant substances within any coal deposit; probably all plant products enter into coal to some degree in more or less altered form.

DECAY BY FUNGI

Although we know that a wide variety of fungi were present during Paleozoic time, evidences of fungal remains are relatively very rare and obscure in coals of this age. *Bona fide* sclerotia are so rare in all the Paleozoic coals I have examined that their general abundance in Cretaceous and Tertiary coals is emphasized all the more as a significant feature. A similar conclusion is evident on observation of the vegetative mycelium of fungi. I have been able to verify personally the presence of a sparse mycelium in a few plant fragments in Paleozoic coals, but in these I have not been confident the mycelium was saprophytic rather than parasitic. On the other hand, observation of a few sections made from attrital components of the younger coals hardly ever fails to disclose mycelium in some abundance. Fragments of fungal mycelium often withstand maceration techniques and can be observed frequently in residues prepared from most of the younger coals. So far as my own observations go, and I have studied many more Paleozoic than Mesozoic or Tertiary coals by this method, fungal mycelium is extremely rare if it is present at all in the residues prepared from the Paleozoic coals. Perhaps some allowance should be made for differences in maceration required because of common differences in degree of metamorphism and development of rank; however, results derived by maceration are entirely consistent with observations made from thin sections of coal that has not been subject to any alteration or chemical treatment.

Confronted with these observed differences, it seems we can conclude that fungal decay played a much more subordinate role in decay of Paleozoic coals than in coals formed in later epochs. Saprophytic fungi are principally aerobic organisms, and I interpret this difference in their occurrence to indicate a much more persistent or frequent aerobic exposure of the Tertiary and Cretaceous peat than occurred in the peat swamps of Paleozoic times. A significant contrast in microbiologic environments must be responsible for these differences.

MECHANICAL DEGRADATION

Other differences also may be cited to suggest that the effects of decay were somewhat different in the Paleozoic. The fine debris produced by mechanical attrition of plant fragments weakened by decay was mentioned previously. Production of these shreds and particles, sometimes consisting of only a cell wall fragment, may in any given instance be completely independent of any microbiologic cause. However, conditions that favor decay also will favor production of a larger amount of the comminuted plant fragments. The fine debris in coals petrographically analyzed by the

Thiessen method may thus be regarded as a partial reflection of the extent of decay.

Two types of attritus are conventionally determined by Thiessen's procedure: opaque attritus and translucent attritus. In coal utilization these different fractions of the coal have vastly differing significance, but for the present purpose of expressing only a degree of textural degradation, these two values may be combined.

Determination of opaque and of translucent attritus excludes practically all the individual plant fragments that are thicker than 14 microns along the vertical line of microscopic transect.[2] In the peaty condition all these fragments occupied a somewhat greater space, but this standard, adopted for other reasons, should be none the less appropriate for the present purpose.

Analyses that are probably suitable for comparison of combined opaque and translucent attritus percentages are available for about 100 column specimens of banded coal of Paleozoic age in the United States (various U.S. Bureau of Mines publications on coal constitution). For these coals the combined values average slightly more than 40 per cent.

Based on about 25 analyses, the equivalent figure for coals of Cretaceous age is approximately 58 per cent.

Fewer comparable analyses are available for the coal beds (mostly of lignitic rank) of Tertiary age, and the comparison is complicated further by the presence of two rather strongly contrasting type-groups, one of which—the woody lignite—is not comparable on botanical grounds with most Paleozoic coal. Woody lignite from Montana and Dakota is represented in six analyses in which combined opaque and translucent attritus composes, on the average, about 38 per cent of the coal. The coals of Tertiary age not dominantly woody, on the other hand, such as those from Alaska, include in the neighborhood of 60 per cent combined translucent and opaque attritus. Almost all coals of this latter type-group include a singular abundance of the remains of fossil fungi. A column profile of a thick lignite bed from Alaska (Suntrana mine) is illustrated by figure 3, which is based on a study made by the author and H. J. O'Donnell at the U.S. Bureau of Mines.

The consistently uniform development of this coal is to be noted. One hundred and forty-eight thin sections were studied for purposes of this analysis. The two bar series in the center of the divided chart represent translucent and opaque attritus. Reading left to right, we observe the former is more abundant in nearly all the thin sections studied.

About 50 analyses of this type are available, all told, for coal beds of both Cretaceous and Tertiary age. The average combined opaque and translucent attritus in these amounts to about 56 per cent. If coals of dominantly woody composition were excluded, this figure would be considerably higher.

As indicated in an earlier section of this paper, the heavy xylem cylinders of peat-swamp trees appear to have a better chance to escape extensive decay, through rapid submergence below the water table. This effect probably was not comparably represented in the many Paleozoic coals composed of plants that lacked a heavy cylinder of wood, and consequently some allowance should be made to present a more correct comparison between the coals formed in different ages. For the present purpose it may be sufficient to suggest that the contrast in amount of combined translucent and opaque attritus in Paleozoic coals, as compared with younger coals, must be *somewhat in excess* of the ratio of 40 to 56 that is indicated here. It is

[2] *Combined values* of opaque and translucent attritus are based entirely on determinations of quantitative microscopy. Hence this combination is different quantitatively, and should not be confused with the values sometimes given for "*attrital coal*," which is estimated by megascopic standards and includes a substantially coarser textured fraction (including some anthraxylon or microvitrain) than the conventional microscopic entities.

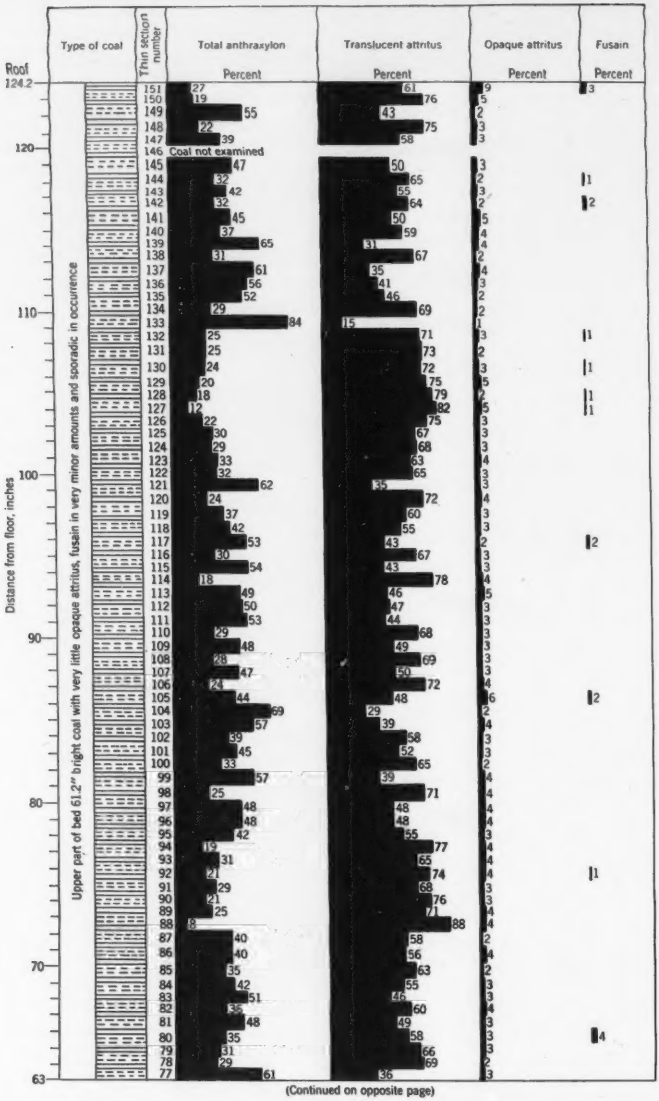
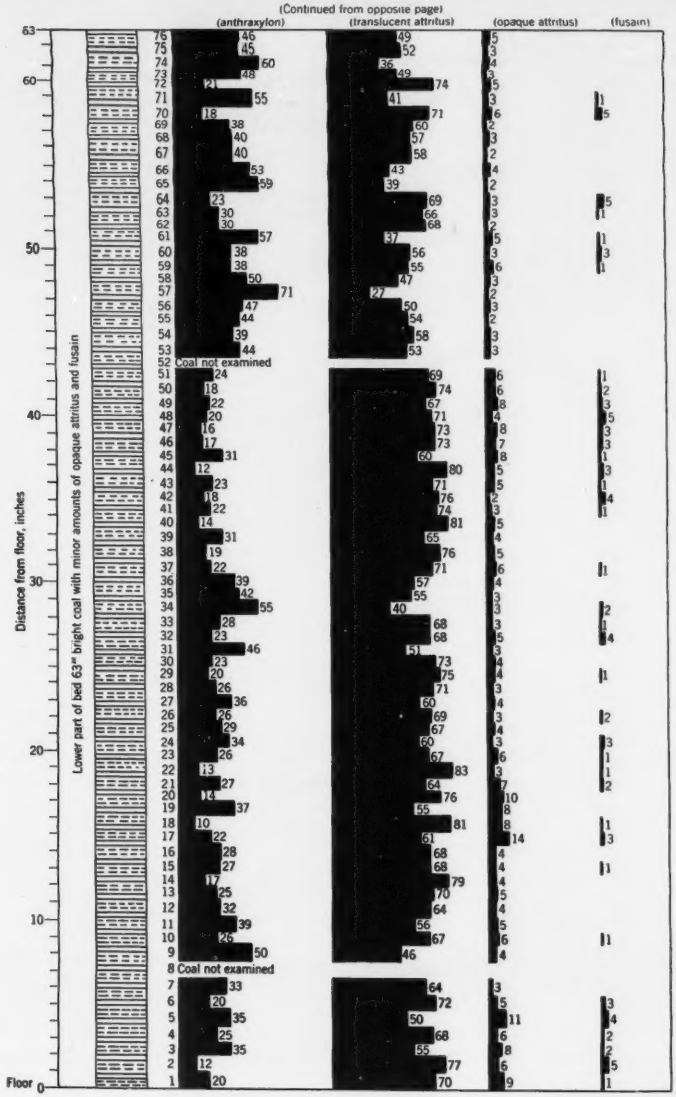


FIG. 3.—Petrographic composition of Suntrana no. 3 coal bed, Healy River, Nenana District, Alaska. Figure prepared by Graphic Section, U. S. Bureau of Mines, under supervision of Mr. L. F. Perry.


(Continued from opposite page)
(anthraxylon)
(translucent attritus)
(opaque attritus)
(fusain)
Distance from floor, inches
Lower part of bed 63" bright coal with minor amounts of opaque attritus and fusain
Coal not examined
Coal not examined
Floor

my belief that these figures possess a general significance in indicating the usual extent of degradation that entered into formation of coals of these different ages.

ANAEROBIC DECAY

It seems possible that the sulfur content of coal may give an indirect indication of the extent of anaerobic decay. Pyrites usually are the source of any large amount of sulfur determined in routine coal analyses. Small amounts of sulfur are in organic combination in coal, and occasionally gypsum or even free sulfur may be present. Nevertheless, primarily deposited pyrites are commonly the source of most of the sulfur in coal, and variation in total sulfur content is due largely to variations in the amounts of such pyrites. These pyrites are deposited principally as a result of combination of hydrogen sulfide produced in fermentation, with iron supplied by waters of the peat swamp. It also must be noted, however, that secondary as well as primary pyrites occur in coal and that such secondary deposits may bear no relation to decay within the bed of peat. Furthermore, a good deal of hydrogen sulfide probably passed off from the peat in a gaseous form; a few coal beds are known which, in a fairly advanced stage of metamorphism, still yield free hydrogen sulfide, the gas apparently being occluded in the coal.

These various considerations suggest that it would be extremely hazardous to attempt to interpret relative degree of decay on the basis of sulfur content in any specific instance. The objections that can be raised against the use of this simple criterion in any given example of coal are valid. Nevertheless, I believe a generalization based on average sulfur content is probably as satisfactory an indication of the general importance of anaerobic decay as is available at the present time. There is no question as to the reality of the sulfide deposition in putrifactive fermentation, but invariably complications of both an analytic and geologic nature seem to render quantitative interpretation dubious and proof difficult, if not impossible, in application to any specific deposit.

The average sulfur content of Paleozoic coal is considerably higher than that of coal of Cretaceous and Tertiary age. A considerable number of analyses of face samples of coals of different ages are available, and a preliminary sampling of sulfur determinations has yielded the following results, expressed on a moisture-free basis:

	Per Cent
Paleozoic coal	2.3
Cretaceous coal	1.3
Tertiary coal	0.7

This general trend may be interpreted to indicate that anaerobic decay was considerably more important information of Paleozoic than in Cretaceous or Tertiary age coal. The actual figures cannot be taken to have any specific significance, but it seems likely that the trend indicated has a fundamental bearing.

CONCLUSION

On this tentative basis, I suggest that anaerobic decay was probably more important during accumulation of Paleozoic peat than during accumulation of equivalent later deposits. This conclusion would be in keeping with the inference, made earlier, that a more consistently higher water table was responsible for lesser fungal decay in the Paleozoic deposits. Anaerobic processes would be favored if the water table was at a high level while the deposit was unconsolidated. I think it also would be reasonable to expect a reversal of these general conditions during the Cretaceous and Tertiary, when the original areas of peat accumulation tended to be less continuously widespread.

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FIGS. 1–7, JUNE, 1952

ANALCIME IN THE POPO AGIE MEMBER OF THE CHUGWATER FORMATION

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University of Missouri, Columbia Missouri

ABSTRACT

Analcime has been determined to be a prominent and characteristic mineral in the Popo Agie "beds," a member of the Chugwater formation. It is responsible for the distinctive lithology and physical properties which set out the Popo Agie from other western Mesozoic red beds. The analcime-containing beds are up to 60 feet in thickness and are wide-spread in western Wyoming. Only one other sedimentary occurrence of comparably large quantity of analcime has been reported, parts of the Green River formation.

The analcime in the Popo Agie is believed to have originated from the interaction of hydrous aluminum silicate clay minerals with sodium-rich waters of a large interior marsh-lake. It probably represents an aluminum silicate mineral stable under the special saline environment, analogous to certain clay minerals which are stable under soil-forming or marine environments.

The analcime-bearing strata constitute a stratigraphic marker within a red bed sequence which, because of insufficient fossil zones or physical datum beds, has been perplexing in stratigraphic studies. It may aid in future stratigraphic work.

The large quantity of analcime available invites the attention of industrial mineralogists. Included in its zeolitic properties is the capacity to react with acid and release silica gel and recoverable aluminum compounds.

INTRODUCTION

That "analcite is rare in sedimentary rocks, but its occurrence of extensive beds is even more remarkable," was written by Wilmot H. Bradley (1929) when he called attention to the large scale occurrence of analcime in the Green River formation in Wyoming and elsewhere. Special interest attaches therefore to the recognition of a second widespread occurrence of analcime in thick beds in another sedimentary formation also in Wyoming.

The Popo Agie[1] member (Triassic) of the Chugwater formation where typically developed is made up characteristically (and dominantly over much of its occurrence) of analcime, which is accompanied by accessory quartz, alkaline-earth carbonates, and iron oxides. A thickness ranging between 40 and 60 feet of continuous analcime-bearing section almost encircles the Wind River Mountains. Indeed, the analcime-bearing beds are so extensive and mineralogically characteristic that the stratigraphic boundaries of the Popo Agie may well be described and limited by the analcime, just as the thinner Alcova limestone, for example, is identified on a basis of its lithology and carbonate mineralogy.

[1] Pronounced popózhie.

IDENTIFICATION OF THE ANALCIME

Analcime was first recognized by the writer in museum-collection (University of Missouri) hand specimens of the Popo Agie in early 1951, during a clay mineral survey of various shales and claystones. The uncommonness of sedimentary analcime stimulated further study, field collecting, and additional laboratory work on the Popo Agie. Because the presence of analcime has not been mentioned previously in the Popo Agie member although extensive stratigraphic studies of it have been made, and because analcime is probably less familiar to most field geologists than is calcite, for example, identifying characteristics will be given.

Analcime (*analcite* was disapproved as the mineral name by a British-American mineralogical committee on nomencla-

FIG. 1.—X-ray powder diffraction diagrams of analcime (Cyclopean Islands, Italy), and of Popo Agie specimen from Circle Ridge Dome bed No. 4. Coincidence of lines in the Popo Agie pattern with those in the analcime standard indicates the presence of analcime in the Popo Agie material. Extra lines of quartz (one is indicated by "Q" in the photograph) are caused by the quartz silt in the Popo Agie. Chromium Kα radiation.

ture) is a zeolite with a theoretical formula, $NaSi_2AlO_6 \cdot H_2O$. It is isotropic to weakly birefringent, having an index of refraction 1.479–1.489. The Popo Agie analcime is isotropic with indices ranging slightly around 1.487.

The X-ray diffraction pattern of analcime is distinctive and clearly diagnostic. A comparison of patterns from relatively pure "standard" analcime mineral (Cyclopean Islands, Italy) and from a selected Popo Agie sample shows their coincidence, figure 1. The prominent lines of a small amount of accessory quartz are also present in the photograph. Powder diffraction data which were measured and computed on the Popo Agie material were found to be in close accord in spacings and intensities with the A.S.T.M. X-ray reference data on analcime, but they are not repeated here in order to save space.

A chemical analysis made of the coarse oolitic part of a specimen collected at Maverick Springs oil field is given below. A photograph of part of that hand specimen is shown in figure 2, and a photo-micrograph of its thin section in figure 3 A.

Weight per cent is given in column 1 of the table of analyses, and the oxide molecular ratios in column 2. The mineral composition of the specimen is then calculated by assigning all of the Al_2O_3 to

TABLE OF ANALYSES

	1 Coarse oolite, Maverick Springs[a]	2 Oxide mol. ratios	3 Al_2O_3 as unity	4 Excess (+) or Deficiency (−)	5 Analcime Arizona[b]
SiO_2	56.07	935	756	+179	58.8
Al_2O_3	19.34	189	189	—	17.9
Fe_2O_3	3.58	23		+ 23	2.2
TiO_2	0.49	6		+ 6	
CaO	0.64	12	8	4 to $CaCO_3$	0.5
MgO	0.36	9	9		0.8
K_2O	3.47	37	37 (187)	− 2	1.5
Na_2O	8.24	133	133		9.8
Loss Ig.	7.50	H_2O—407	378	+ 29	H_2O+8.6
CO_2	0.18	4			FeO 0.1
SO_3	None	—			
P_2O_5	0.10	1			
	99.97				100.2

[a] Analysis by Bruce Williams Laboratory, Joplin, Mo.
[b] Analcime, Yavapai County, Arizona C. S. Ross, 1928.

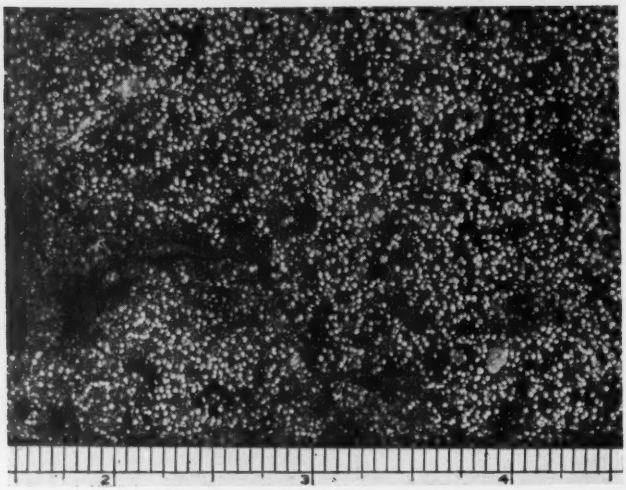

FIG. 2.—Photograph of oolitic hand specimen of Popo Agie from Maverick Springs Dome locality. Scale in inches.

analcime. Sufficient CaO is allotted to take care of CO_2. The CO_2 is subtracted from Loss on Ignition and the remainder computed as H_2O, 407.

The remaining CaO, MgO, K_2O, and Na_2O are added, column 3, which gives a molecular ratio of 187 to 189 for Al_2O_3, a fortuitously close ratio of theoretical 1:1. Fe_2O_3 is in excess, column 4, but the yellowish red color of the specimen would indicate free iron oxide.

Silica and water are also in obvious excess, but Dana-Ford mineralogy reports for analcime (p. 653), "Analyses show always a varying excess of silica and water above amounts required by the formula." The quartz silt seen in the thin section accounts for part of the excess silica.

K_2O is notably high in the analysis, almost high enough to be considered a source of potassium for fertilizer use.

In column 5 is repeated the analysis of analcite sample II from Ross (1928) for purposes of comparison.

MICROSCOPIC DESCRIPTION

Twenty-three thin sections of ocherous and oolitic Popo Agie and its nodules and associated rocks were studied. Typical oolites showing concentric structure may be developed in the analcime, as in figure 3C. They are abundant in the size range ¼ mm to 1 mm in diameter. These are oolites (Tarr, 1918) in the regular sense of the word and differ from the analcime crystals of oolite size as were found in the Green River formation by Bradley.

Oolites may have grown singly and independently, or clusters of them may have grown close together so as to interfere and be joined by interpenetrating sutured contacts, figure 3C. Subsequent deformation of oolites, and the formation of microstylolites by interpenetration and solution is shown in figure 3D.

Clusters of quartz silt cemented by spheres of analcime without concentric structure are also common, figure 3B. In some places the analcime grew as linear, slightly plumose, extensions through the

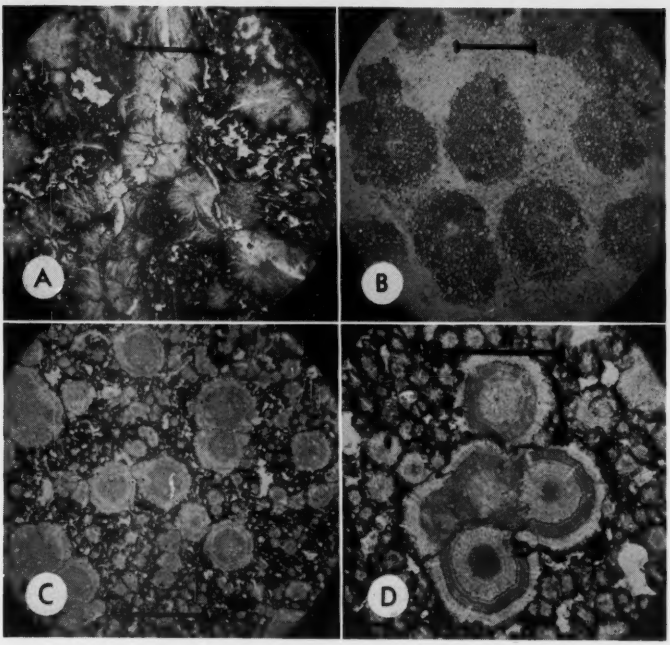

FIG. 3.—Photomicrographs of thin sections of analcime rock. All transmitted light, uncrossed Nicols. Length of inked line indicates 1 mm.

A. Analcime in branching pattern formed by coalescence of round, oolite-like bodies. Also tiny veins of clear secondary (?) analcime and carbonate interspersed within and cutting earlier analcime. Dark areas are iron oxide-stained analcime between the "oolites." Maverick Springs locality.

B. Clusters of fine quartz silt cemented by analcime which appears dark and in high relief because of its low index of refraction. Remainder of section contains quartz silt without analcime cement. Popo Agie River locality (proposed type locality).

C. Oolites of relatively clean analcime set in a matrix of iron oxide-stained analcime. Note concentric structure of oolites, single oolites, and coalesced multiple oolites joined in a suture pattern. Popo Agie River locality.

D. Microstylolites between large oolites and extending slightly outward. Note various sizes of the oolites and oolite-like bodies (lacking concentric structure). Popo Agie River locality.

coalescence of segregated bodies of analcime which may or may not show concentric growth, figure 3A. If concentric structure is necessary for the names oolite or ooid to apply, perhaps these bodies without the structure may be called *quasi-oolites*. Such structures have been observed in limestone and chert, and are certainly not uncommon.

The writer interprets these tiny spheroidal bodies (oolites and quasi-oolites) as having grown and accumulated in a gel or ooze whose composition approached that of analcime. Where the environment included diffusion of iron compounds, concentric zoning occurred. Carbonate grains may fill in between analcime oolites, and small amounts of highly birefringent carbonate dust may occur within some of the analcime. Short

FIG. 4.—Outcrop of the Popo Agie member ("beds") on Middle Fork of Popo Agie River, State Experimental Farm, sec. 3, T. 32 N., R. 100 W., the proposed type locality. The Popo Agie is overlain by tan (thin layer at base) and reddish Nugget (Wyopo) sandstone.

veins both of calcite and clear, weakly bi-refringent analcime (presumably secondary) may cut across iron oxide-stained early analcime, figure 3A. Fine, angular quartz silt and clay particles are abundantly scattered, usually without significant segregation, throughout the analcime. The size of the quartz particles in the analcime ranges from 150 microns in cross section downward to the limit of resolution of the microscope but sizes up to 50 microns are most common. In the subjacent, fissile shale the proportion of coarser quartz grains, 50 to 75 microns in cross section, is notably larger.

LITHOLOGY OF THE POPO AGIE

The "Popo Agie beds" were so named by Williston (1904) from occurrences on the "Popo Agie River, along whose branches they are most characteristically shown" (p. 688). Love (1939), recognizing that the term "beds" implies no definite stratigraphic rank, raised the Popo Agie sequence to the rank of a member of the Chugwater formation. No type locality was ever proposed in print for the Popo Agie member, but the late E. B. Branson, who had worked with Williston at Chicago, and who had supervised many University of Missouri field trips in the Lander region, regularly spoke of the section well exposed in the banks eroded by the Popo Agie River at the State Experimental Farm, about 5 miles southwest of Lander, as the type locality. This exposure includes about 60 feet of analcime-containing beds, and carries the well developed, ocherous and oolitic lithology which has been characteristically identified with the Popo Agie. Fossil bone of the kind described by Williston has been found at this exposure. Therefore, the section exposed just below the farm buildings at the State Experimental Farm, sec. 3, T. 32N., R. 100 W., is proposed as the type section of the Popo Agie member (fig. 4).

The Popo Agie, although set in the midst of silty shales and sandstones within the Chugwater Triassic red beds, is easily distinguished from the strata above and below by the differences in lithology. Whereas the shales are red and fissile, and the sandstones are coarse-textured, cross-laminated, and bedded, the Popo Agie beds are massive, nodular, ocherous and oolitic. The Popo Agie is commonly more resistant to weathering than the shales and may stand above them in steep faces, but it is less resistant than the cliff-forming Nugget (Wyopo,

FIG. 5.—Weathering of massive Popo Agie along joints to produce rounded block and boulders. Hammer in center of photo indicates size of the blocks. Exposure is about 1 mile northwest of locality in figure 4.

Branson and Branson, 1941) sandstone which overlies it in the Lander region.

The Popo Agie is light to dark tan in color in most places, but may be brownish, greenish, or even very dark gray (locally almost black). The colors are ocherous yet usually soft, somewhat pastel. Oolitic texture is common, in which oolites of a lighter hue are set in the darker-colored matrix.

The Popo Agie is not evenly bedded in the usual sense of sedimentary stratification. It is typically massive, but on the face of a massive ledge it may be cut by joints, deepened by weathering, into lenses or beds with undulating margins which rise or droop from horizontality. Furthermore, gradual color changes within fifty to three hundred feet laterally may give rise to additional color wedges or lenses. Secondary joints may cut the massive ledge into blocks up to 18 inches long, which are rounded at the corners through additional weathering (fig. 5). They give rise to nodule-like boulder fragments which upon further weathering, spall, flake, exfoliate, and disintegrate into smaller fragments. They do not slake like clay-rich shales or claystones do upon wetting, although the Popo Agie superficially does resemble a claystone.

Some parts of the massive Popo Agie are softer, more friable, and less well bonded than others. These beds crumble and break apart to wash and roll down a weathered slope of sandy and gravelly fragments which retains the color of the original rock (fig. 6).

The distinctive lithology of the Popo Agie was previously described as that of "ochre clays" (Love, 1939), "sandy shale" (Tarr, 1918), "oolitic claystone" (Branson and Branson, 1941), "mudstone (Branson, 1915), and "siltstone and claystone" (Love, Tourtelot, *et al*, 1947). Boulders of the Popo Agie are compact, and appear tough when hit with a hammer. The iron oxide pigment, earthy luster, and fine grain of the rock make it resemble a clay stone. The analcime accounts for the rock's resistance to slaking, its tight bonding, structural strength and response to weathering. Clay minerals are relatively scanty in the Popo Agie. The distinctive physical properties of the Popo Agie are due to its mineral constituent—analcime. It is no wonder that the properties did not accord with those of claystone, and that the Popo Agie did not fit in the clay sediment category.

In addition to the previously described, rough-textured Popo Agie, a well-defined

zone of fine-grained, sub-lithographic stone, usually tan in color, occurs in some places at the top of the member. Where present, it ranges in thickness from a few inches, as at Derby Dome south of Lander, to twenty or more feet, as at Circle Ridge Dome in the southwest end of the Owl Creek Mountains. Mineralogically, this rock may be fine-grained dolomite or may be dominantly analcime. Apparently the two mineral zones intergrade. They may be differentiated in the field by the usual dilute HCl acid test for dolomite; analcime does not effervesce.

Calcite-containing nodules, partly hollow to solid, ranging in size from small pisolites to rounded globes or flattened lenses six inches in diameter occur, usually as concentrations in bed-like zones, throughout the upper part of the Popo Agie. Generally the outer surface of the nodules is rough, irregular, and hard, possibly siliceous.

NOTES ON THE DISTRIBUTION AND STRATIGRAPHY OF THE ANALCIME

This investigation began primarily as a mineralogical study of the ocherous and oolitic Popo Agie, and field collecting was planned with that objective in mind. As the study proceeded and the problem widened, it appeared that the distribution of the analcime has important stratigraphic significance. For the sake of stratigraphic completeness the collecting should have been extended to the geographic limits of the analcime distribution. Although such exhaustive study was not made, the distribution that was sampled will give an idea of the wide-spread character of the analcime and its usefulness as a stratigraphic marker. Several measured sections will be described, the proposed type section in greatest detail.

Section at Wyoming State Experimental Farm.—The section of the Popo Agie at the State Experimental Farm (proposed type locality) about 5 miles southwest of Lander, Wyoming in sec. 3, T. 32 N., R. 100 W., is exposed as follows.

Nugget (Wyopo) sandstone. Basal layer, slightly conglomeratic, white to gray fine-grained quartz sandstone, thinly laminated with red-stained sand.

Popo Agie. Ocherous, earthy, analcime-containing rock which resembles superficially a claystone. The presence of analcime in each zone described below was confirmed by X-ray diffraction. These zones which are identified by texture and color, vary sufficiently in thickness by interfingering that sections measured 300 feet apart laterally might vary considerably in details. In descending order they are:

	Thickness
1. Mottled yellowish gray (between 5 Y 7/2[1] and 5 Y 6/4), oolitic, earthy massive, quartzose analcime rock	0 to 3′
2. Light tan (between 5 Y 7/6 and 5 Y 6/4), oolitic, massive, earthy, gritty analcime with calcite lined vugs ½″ to 2″ in diameter	3′ to 4′
3. Yellowish brown (near 10 YR 5/4), light tan oolites, earthy, massive, quartzose analcime	6′
4. Dark red (between 5 R 4/2 and 10 R 3/4), soft, friable, coarse-textured, oolitic, massive earthy, quartzose analcime	6′
5. Tan, (near "grayish orange pink 5 YR 7/2), oolitic, rudely laminated and jointed. Resistant to weathering. Locally becomes pinkish red. Contains sporadic calcite nodules	0 to 14′
6. Pale red (near 5R 6/2), oolitic, poorly bedded, soft, friable, crumbly, quartzose analcime. Contains several discontinuous layers of resistant (siliceous?) nodules 1″ to 30″ in diameter	20′ to 25′
7. Pale red (near 10 R 6/2), oolitic, earthy, resistant ledge	4″ to 2′
8. Grayish red purple (near 5 R P 4/2), oolitic, with thin wavy, nearly horizontal light bluish gray (5 B 7/1) bands up to 1″ thick and 1′ long. Soft and friable, earthy quartzose analcime rock	12′
Thickness exposed	60′+

[1] Notation refers to Rock Color Chart, National Research Council, Washington, D.C. (1948).

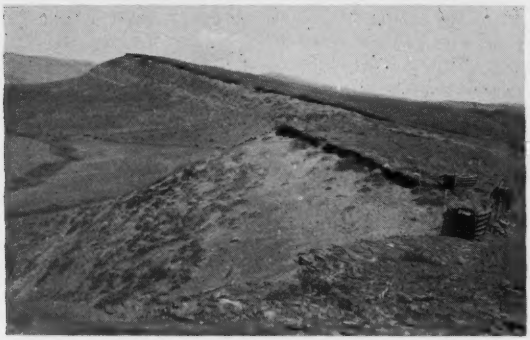

FIG. 6.—Weathering of the Popo Agie beneath the resistant dipping Nugget (Wyopo) sandstone to a steep but relatively smooth, gravelly back slope. Photo taken about 2 miles northwest of locality in figure 4.

Popo Agie River stream bed. Actual base of analcime rock not exposed, but by projecting up dip about 250 feet to other exposures it is obvious that the contact with the subjacent red silty shale (termed Crow Mountain by Branson and Branson, see explanation below) must occur very close to the surface of the river water at the location of measured Popo Agie.

Crow Mountain. Red (between 5 R 6/2 and 5 R 5/4) silty, quartz-rich, laminated shale.

Branson and Branson (1941, p. 135) referred the red, silty shale sequence lying between the top of the Alcova and below the base of the "oolitic claystone" (their Popo Agie) in the Lander region to the Crow Mountain. This differs in color and lithology from the type Crow Mountain as named by Love (1939, p. 44). Whether or not the two rocks are stratigraphically equivalent is beyond the scope of this paper. If they are not, the red shale in the Lander region is unnamed, but for the purpose of designating its relative vertical position in this paper, the usage by Branson and Branson is followed.

Section near Dubois, Wyoming.—Nine samples of ocherous Popo Agie were collected where its outcrop is crossed by U. S. Highway 287 about 12 miles southeast of Dubois, Wyoming. Section is recorded top uppermost. Analcime was found in every zone by X-ray diffraction patterns.

	Thickness
Conglomerate. Reworked, rounded pebbles and granules up to 1½″ in cross section like tan zone No. 4 below, set in a calcareous, gritty, clayey matrix	3″ to 4″
1. Tan, resistant, silty analcime layer containing small nodules and clacite-lined vugs	3′
2. Deep red, fine-grained, almost lithographic-like, analcime and dolomite	5′
3. Tan colored, otherwise similar to zone above	20′
4. Light brownish red, rough-textured, dull, earthy, quartzose analcime. Weathers to rough pebbly surface	15′
5. Yellowish brown, oolitic resistant ledge, slightly nodular, scant quartz silt, mostly analcime	2½′
6. Brownish red, oolitic, friable zone, weathers to coarse, sand-size detritus. Silty quartzose analcime	1½′
7. Dark tan, coarse oolitic texture, prominent resistant analcime ledge	10′ to 12′
8. Brownish red, coarse oolites. Massive, poorly resistant to weathering friable, quartzose analcime	15′
9. Base not exposed	
Exposed thickness	70′+

Popo Agie near Red Rocks Ranch on Gros Ventre River, about 20 miles east of Moose, Wyoming.—High on the cliffs on the north side of the Gros Ventre River, across from Red Rocks Ranch the ocherous Popo Agie is spottily exposed near a faulted zone. At least 15 feet, and perhaps a 30-foot thickness, or more, is present. Three spot samples of yellowish, reddish, and dark gray to black Popo Agie were collected where small gullies had cut through the cover of slope-washed detritus. The specimens are typically ocherous, dull, earthy, and slightly speckled with sporadic oolites. All three gave analcime diffraction patterns. This locality is the farthest west sampled.

Section at Circle Ridge Dome, southwest end of Owl Creek Mountains, sec. 6, T. 6 N., R. 2 W.—The Popo Agie beds, which here underlie the Gypsum Spring member, stand nearly vertical at the southeast rim of Circle Ridge Dome. Seven samples were collected representative of zones differing in color or texture of the ocherous, non-laminated rock lying below the conglomerate at the top. All of them contain analcime as indicated by X-ray.

The fissile red shale beneath the massive analcime rock does not contain analcime.

	Thickness
Gypsum Spring. Basal conglomerate composed of small pebbles and granules of ocherous Popo Agie set in a matrix composed of gypsum, calcite, and silica....	4″
Popo Agie. 1. Rich tan-colored, fine-grained, sub-lithographic, earthy ocherous analcime and dolomite rock. Irregularly bedded in layers 1″ to 4″ thick. Breaks with conchoidal fracture. Layer of nodules 2″ to 8″ in diameter about 18 feet below top.....	20′
2. Like above, but less resistant thinner bedded.....	23′
3. Transition layer between No. 2 above and reddish zone No. 4 below.....	18″ to 24″
4. Brownish red, rough-textured, resistant, prominent ledge of slightly quartzose analcime rock. Varies in color along the strike. May be sparsely oolitic, and may carry nodules locally. Contact with subjacent shale not visible, but red, fissile shale is exposed 10 feet stratigraphically lower in gulley.....	20′+
Thickness exposed.....	65′+

Maverick Springs Dome.—The ocherous Popo Agie is well developed at Maverick Springs Dome where erosion has cut down at the center of the dome to the Popo Agie. Detailed collecting was not done here because it was thought the section would be similar to that at the nearby Circle Ridge Dome. Two spot samples from near the base of the ocherous part were taken; one is pictured in figures 2 and 3A. Both samples contained analcime.

Derby Dome, about 13 miles south east of Lander, Wyoming.—The Popo Agie is well exposed high in the north rim of Derby Dome. The presence of analcime in these samples was confirmed by X-ray diffraction.

	Thickness
Nugget (Wyopo) sandstone.	
Popo Agie 1. Irregular zone of tan, fine-grained analcime-dolomite rock, irregular calcite nodules in clayey matrix, and transition to red material below.....	4′+
2. Dark grayish red, slightly oolitic, fine-grained earthy, massive analcime rock. Weathers into blocks which round at corners to become boulders 8″ and less in diameter.....	4′
3. Like No. 2 but purplish red, coarse texture, abundantly oolitic.....	5′
4. Dark red, rough coarse-textured, oolitic, friable, quartzose analcime. Weathers to gravelly slope. Base not exposed.....	10′+
Crow Mountain shale below	

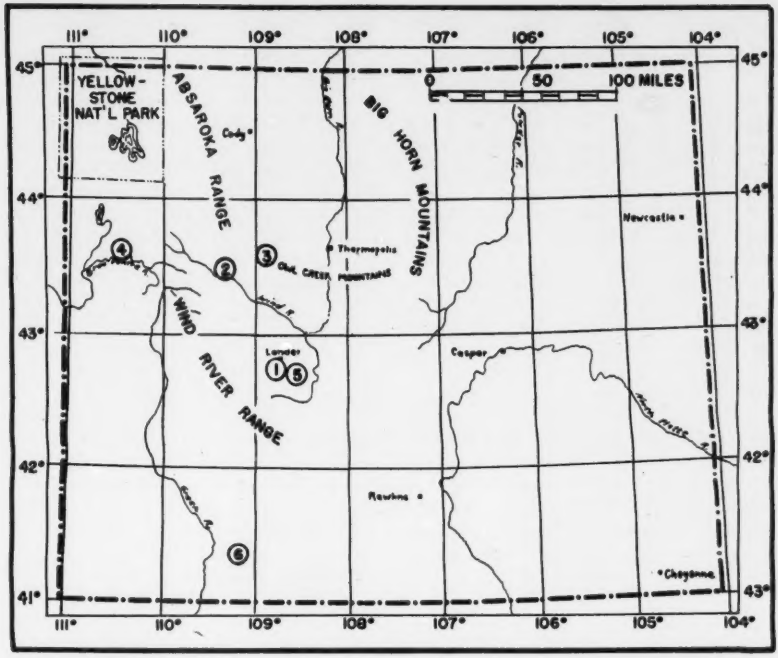

FIG. 7.—Outline map of Wyoming showing the localities sampled. (1) On Middle Fork of Popo Agie River about 5 miles southwest of Lander. "Sinks Canyon." (2) On U.S. Highway No. 287, about 12 miles east of Dubois. (3) Southeast corner of Circle Ridge Dome (oil field). (4) North of Red Rocks Ranch, about 20 miles east of Moose. (5) North rim of Derby Dome (oil field) about 13 miles southeast of Lander. (6) Unit Well #1, Mountain Fuel Supply Co., South Baxter Basin, sec. 21, T. 16 N., R. 104 W.

Subsurface near Rock Springs, Wyoming.—Analcime-bearing, ocherous, oolitic Popo Agie, 40 feet thick, occurs between 4,665 and 4,705 foot depths in Unit Well #1, Mountain Fuel Supply Company, South Baxter Basin, sec. 21, T. 16 N., R. 104 W., near Rock Springs, Wyoming, as shown by cuttings from the well furnished through the courtesy of Mr. M. M. Fidlar, Mountain Fuel Supply Co. The analcime-bearing cuttings are typical of the Popo Agie so described from surface outcrops. Yellowish, reddish, purplish, greenish, and grayish, ocherous oolitic, fine-grained, earthy, non-fissile chips were crushed by the drill bit similar to weathered and broken fragments from the outcrop. Each sample at 5-foot intervals showed the presence of analcime (also usually quartz) in X-ray patterns.

Localities at which the analcime-bearing Popo Agie was found are shown on the accompanying map of Wyoming, figure 7. A triangle with corners at Lander, Moose, and Rock Springs covers an area of about 6,000 square miles. Presumably the analcime was deposited over a minimum area which included the Wind River Basin to the north, across the Wind River Range to the southwest, with probably an actual wider extent.

To this point, J. D. Love (personal communication, 1951) advised, "The ocher beds are developed also about 5 miles east of the southern entrance to Yellowstone Park. . . . I am told that in Manila, Utah section ocher beds are present at the base of the Nugget sandstone but have not observed this myself."

Although specimens from the Yellowstone Park and Manila, Utah localities have not been analyzed mineralogically for analcime, the writer expects that it does occur in those *ocherous* rocks, because not a single specimen sample of the oolitic, rough, earthy, ocherous typical Popo Agie collected by the writer failed to give a positive test for analcime. Conversely, none of the associated fissile red shale and sandstone in other parts of the Chugwater did show it. Hence considerable confidence has been developed in the association between analcime and the ocher beds, which are presumed to have even wider distribution than was actually observed.

STRATIGRAPHIC RELATIONS OF THE POPO AGIE

The ocherous and oolitic Popo Agie beds, the lithology upon which there is no stratigraphic disagreement, are overlain in the Lander region by 200 feet of Nugget (Wyopo, Branson and Branson, 1941) sandstone. In the Lander oil field, also called locally the Hudson Dome because of its proximity to the town of Hudson, and at Derby Dome, a layer of fine-grained, sub-lithographic, compact, earthy yellowish dolomite, and analcime with dolomite intervene between the oolitic phase and the Nugget. This earthy, yellowish oxidized-appearing rock does not necessarily derive its lithologic characteristics from surface weathering, as has been suggested upon casual examination; the lithology appears to be inherent in its genesis.

At Circle Ridge Dome a gypsiferous conglomerate containing Popo Agie pebbles, succeeded by the Gypsum Spring gypsum, overlies the fine-grained dolomitic analcime rock of the Popo Agie. Near Dubois, gray shale and superjacent sandstone succeed the conglomerate resting on the top bed (coarse-textured) of Popo Agie. Neither the Wyopo nor the Gypsum Spring is present here. In the South Baxter Basin well, interbedded shale and sandstone are logged immediately above the Popo Agie interval. Detailed studies of the Chugwater by M. G. Mehl are in progress (personal communication, 1951).

ORIGIN OF THE ANALCIME

A sound theory for the origin of the analcime must explain and provide a source for its sodium, aluminum, and silica; its associated quartz silt and pigmenting iron oxide; its wide-spread distribution and considerable thickness; and its content of reptilian, amphibian, and Unio remains (Williston, 1904; Branson and Branson, 1941; Branson and Mehl, 1929). These factors will be considered after earlier ideas on the origin of sedimentary analcime are reviewed.

The analcime in the Green River formation was found by Bradley (1929) to be associated with volcanic mineral fragments, and he concluded that the analcime formed in place on a lake bottom as a result of interactions between salts dissolved in the lake water and the dissolution products of volcanic ash that fell into the lake. Ross (1928) described analcime from playa lake deposits in Yavapai County, Arizona, and offered alternative explanations for its origin: (1) similar to that later expressed by Bradley, and (2) reaction between sodium salts concentrated in the playa lake and the hydrous aluminum silicates in the playa mud.

The origin of the analcime in the Popo Agie can be accounted for logically by the second of Ross' explanations. Although the derivation of aluminum and silica is probably easier to account for chemically from volcanic dust than

from clay minerals, yet no evidence of volcanic material was found. Careful search in the thin sections from the Popo Agie failed to locate any shards, feldspar, mica, or other fragments indicative of volcanic dust. The quartz particles previously mentioned constitute almost all of the coarse clastic material associated with the analcime. Therefore, a volcanic derivation of the aluminum and silica seems improbable because of negative evidence. The possibility is recognized however, that volcanic dust might have been a source of the analcime, and that *all* readily decomposable parts of the dust were altered to analcime, leaving no evidence of its prior existence, but that possibility seems rather remote.

In the absence of a volcanic heritage for the aluminum and silica of the analcime, it is concluded that those elements came from hydrous aluminum silicate clay minerals, such as occur in association with quartz silt in the subjacent fissile shale. In the case of the analcime beds, the clay instead of becoming shale is believed to have reacted with sodium-rich water to form the hydrous sodium aluminum silicate analcime.

The clay mineral determined in one sample studied of the red shale collected a few feet below the lowest outcrop of the analcime at Circle Ridge Dome is montmorillonite (the .001 interplanar spacing expanded to almost 18 A. with ethylene glycol). No analcime was shown by X-ray to occur in this shale sample. Montmorillonite is a relatively highly reactive member of the clay mineral family, and could easily furnish aluminum and silica for analcime. Whether the montmorillonite represents altered volcanic dust can not be determined.

The widespread basin or lowland in which the analcime formed is believed to have been a kind of marsh, or a connected series of playa-like lakes which varied locally in depth and in salinity, iron content, and oxidizing potential.

Whether the sodium in the water was in solution dominantly with the chloride ion, or primarily with carbonate and sulfate ions, which are abundant in some present-day playa lake waters (Clarke, 1924, p. 238) can not be determined positively upon independent evidence. However, the presence of fossil Unios of the fresh water type in the Popo Agie is evidence against marine, high sodium chloride salinity. Moreover, from the viewpoint of chemical reactivity with clay minerals, sodium carbonate and sulfate waters are appealing. The presumption is strong therefore that the Popo Agie water was probably rich in sodium bicarbonate, carbonate, and sulfate, like today's playa water.

It seems logical that analcime was formed because it was the most stable hydrous aluminum silicate in the marsh-lake environment which prevailed during Popo Agie time. It would be analogous to illite which is apparently stable under a typical marine environment: sodium chloride brine, some potassium in solution, and slightly reducing (?) conditions. Reasoning from field evidence, one would expect analcime to be formed under an oxidizing (*cf.* iron oxide in Popo Agie beds), alkaline sedimentary environment where strong sodium-rich carbonate-sulfate solutions reacted with aluminum silicate clays.

The quartz silt which is abundantly dispersed through the analcime rock represents analogous quartz silt which is abundantly associated with clay minerals, alkaline-earth carbonates, and iron oxides in the shales of the Chugwater.

The fossil remains of reptiles, amphibians, and Unios buried in Popo Agie beds are in accord with a fauna which might have lived about a large interior marsh and lake. The Unios are distributed locally, which would imply loci of fresh water sources, like springs and stream inlets. The fossil bone in the Popo Agie is commonly rounded and worn (personal communication, M. G. Mehl) as would result from washing in shallow water.

Imprints of plants in the Popo Agie are of the marsh type of vegetation (from M. G. Mehl).

POSSIBLE ECONOMIC ASPECTS

Large quantities of analcime, although mixed with quartz silt and iron oxides, are available in the Popo Agie. If an industrial use were developed for this zeolite abundant reserves would not be lacking. Industrial mineralogists and technologists might well give it some thought in terms of a zeolite, a colored ceramic flux, a mineral decomposed by acid into silica gel and recoverable aluminum compounds, or for its content of constituent elements.

ACKNOWLEDGMENTS

The writer is grateful to Dr. J. D. Love for information on exposures of the Popo Agie ocher beds, and to Mr. M. M. Fidlar for cuttings from the Mountain Fuel Company well. University of Missouri Research Grants 410 and 415 aided in the field and laboratory work of the problem.

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FIGS. 1–6, JUNE, 1952

TURBIDITY CURRENTS, GRADED AND NON-GRADED DEPOSITS

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ABSTRACT

Conditions of settling are studied theoretically and in part experimentally, and the results are applied to the explanation of various normal and abnormal types of graded and non-graded sandy deposits in deep-water environments. According to the mechanism by which various fossil and recent deep-sea sands have been deposited distinctive features should have been developed, which are tentatively indicated.

INTRODUCTION

The turbidity current mechanism gives a satisfactory explanation for the emplacement of graded graywackes in geosynclines (Kuenen and Migliorini, 1950), more specifically of the macigno sandstones in the Apennines. Natland and Kuenen (1951) applied this explanation to the graded bedding and general sedimentary history of the Ventura Basin in California. Graded bedding found in some North Atlantic cores probably was produced by turbidity currents (Bramlette and Bradley, 1942), as was graded bedding in the San Diego Trough (Shepard, 1951). The grading in glacial varves may be caused by the same mechanism (Kuenen, 1951) although the type of current would be peculiar as it would have to be fed for many weeks on end.

The typical graded bed deposited by a turbidity current is coarsest at the base and grades upwards gradually throughout the entire bed, into the finest material, commonly clay, at the very top. On the other hand, the deposits are "muddy" sands, so the degree of sorting is only moderate in each horizon. This type of grading was nearly always developed in the beds deposited from the experimental turbidity currents studied by the senior author.

However, smaller or greater divergencies from regular grading occur in nature. The aim of the present paper is to examine how far these can be accounted for by the turbidity current mechanism. Experiments with turbidity currents will be described in which non-graded beds are laid down.[1]

ABNORMAL TYPES OF GRADED BEDDING

(1) Natland and Kuenen (1951) pointed out that the majority of sandstones in the Ventura Basin are "muddy" and show regular grading, but that exceptions are not infrequent. The tops of some graded beds are fine sand rather than silt or clay. Other beds grade from coarser to finer upwards but revert in a small distance to coarser again, and either grade regularly to the finer at the top or again revert to coarser texture. Some beds appear to be uniform throughout.

(2) Proximal, sandy varves are usually each laminated with a large number of more or less separate units superposed arbitrarily. Each unit tends to be graded, but indistinctly. Cross-bedding occurs and some horizons are characterized by a large number of pebbles or even cobbles. In distal varves there is no grading in grain size, only in color of the fine clay material, or, according to Arrhenius (1947), the upper winter lamina may even be coarser grained. However, with clay one is never sure that the grain size

[1] The experiments were financed from a grant supplied by the Nederlandse Organisntie voor Zuiver Wetenschnppelyk Onderzoek (Netherlands Organization for Pure Scientific Research).

measured by artificial dispersion is the same as that of the settling particles at the time of deposition.

(3) The authors have seen several deep-sea cores of sandy material of similar appearance to graded deep-sea sands but showing no grading detectable by visual examination. Careful mechanical analyses in some such cores show regular but slight grading (Ericson, Ewing, and Heezen, 1951).

(4) Migliorini has observed that several of the macigno sandstones, especially the thicker ones, show no grading in the lower part although the upper part is regularly graded. The non-graded portion may be a fraction of the total thickness but in some cases more than half (Personal communication).

SETTLING IN STILL AND FLOWING WATER

Before attempting to explain these abnormal types of graded bedding the phenomena of settling in still water and in currents will be briefly reviewed.

If a small amount of unsorted sediment is introduced suddenly at the top of a column of clear water the grains reach the bottom according to their rate of sinking. In the case of spherical particles of uniform density the size gradually diminishes from the bottom of the deposit upwards and a bed with perfect grading from coarse to fine results. In the ideal case each horizon is occupied by only one grain size. Hence the deposit is perfectly sorted in each horizon as well as perfectly graded.

Granular analyses can be made by the use of this principle, the amount of sediment arriving at the bottom of the column of water being either weighed or measured volumetrically at short intervals. In practice, however, difficulties are encountered because groups of grains with the water between tend to form drops of heavy liquid which sink swifter than individual particles, and grains of all sizes are dragged down together. Hence, the sorting at any level becomes imperfect although the grading may still be excellent.

In a stationary cloud of sediment with a uniform mixture throughout the whole column, all grain sizes immediately start to accumulate on the bottom together. The relative amount of each grade as compared to the original composition of the sediment is multiplied by a factor representing its settling velocity. As soon as the largest grains have had time to settle from the surface they are cut out from further deposition and this shift away from coarse progresses until all sediment has settled. Although the absolute amount of each size deposited per unit of time remains equal until it becomes exhausted, the relative amount of the smaller sizes in the deposit increases, because the available range is gradually narrowing. Hence the deposit is graded from the moment all particles of the largest grade have reached the bottom. If the original suspension is formed from a normal sediment the size frequency curve will tail off towards the coarse end and the settling velocity of the largest grains will be a high multiple of that of the median grains. Therefore only a very small proportion of the suspended material will have settled by the time grading begins.

If a cloud of sediment moves in laminar flow, the resulting sedimentation is modified from pure settling only by the introduction of a horizontal dimension. The lower or upper part of the bed may be missing, but the part represented should be the same whether deposited from standing water or a laminar flow.

In a turbulent flow matters are much more complicated. Although gravity exerts the same influence as in standing water, eddies add components of movement and these vary in direction and strength all the time. Towards the surface and bottom these die out and a narrow zone of laminar flow may occur along the bottom.

Although in a stationary mass of water all grains of equal size will reach the bottom from a given level in the same amount of time, this is not the case with a turbulent flow. Some grains happen to

meet more downward than upward eddies and will be carried to the bottom in a shorter time even than required for settling in non-turbulent water, while others remain in suspension longer than the calculated average settling time, because they happen to be caught in more upward than downward eddies. Therefore turbulence not only retards the average time of settling, but spreads a given size over a greater distance of transport than would follow merely from calculating the average settling.

If ineffectiveness of turbulence along the bottom allows sedimentation of grains above a certain diameter, these will gradually be sorted out of the flow and apart from entrapment between the grains a deposit will form from which all finer particles are absent. Pulsations in the current may result in lamination. Complications due to saltation and rolling of the bed load will not be considered here.

It is important to bear in mind that each grain size will show its own distribution of concentration in a turbulent flow from the bottom upwards. The smaller the size the less it will become concentrated towards the bottom. The clay will show almost equal concentration throughout the entire thickness of flow. This relation helps one to understand how a deposit of almost pure sand can be built up by a turbulent flow (river or turbidity current) containing a high percentage of fine material. A river carries most of the lutite it encounters in suspension directly from the source to the point of final deposition, while the sand moves more slowly. The sand is therefore concentrated along the bed and forms a larger part of the load when and where it is in motion. Because of this sorting action of rivers, marine deposits tend to have a higher percentage of lutite than terrestrial sediments. The turbidity current carries all available material until deposition starts and does not concentrate the sand.

The bottom part of a turbidity current moves more rapidly than the upper parts for three reasons. (1) The concentration of sediments towards the bottom is very pronounced in turbidity currents (Kuenen and Migliorini, 1950), so the greater mass of the highly concentrated suspension gives it greater velocity. (2) The excess in hydrostatic pressure between the suspension and the clear water increases downwards. (3) Turbulent mixing along the upper surface retards the flow. An upward flow at the nose of the advancing current results from the vertical velocity gradient. This flow tends to concentrate the coarsest grains in the foremost lower part. As a consequence, the first grains to settle on the bottom from the nose of the flow are also the largest ones that can reach this spot at any time, and as the flow continues to pass over this area the depositing material gradually decreases in size. These relations explain the grading of the deposit. It will presently be shown, however, that they only hold for a current that has been generated suddenly.

With respect to the sorting in each level, the deposit from a turbidity current falls between the two extremes of a deposit dropped through stationary water, which is almost perfectly sorted, and a deposit from a perfectly mixed stationary cloud, in which sorting is restricted to the absence of grains above a certain diameter. In the turbidity current deposit the maximum and median size present in each horizon decrease gradually upwards. At each level, the whole range of still available grain sizes is represented, but the sorting is much more pronounced than in the original suspension. On a horizontal floor the amount of lutite amongst coarse sand grains is quite small when considering that the deposition took place from water with a much higher silt and clay content. On a steep slope the entrapped muddy water might escape later and leave an even cleaner sand.

Four circumstances can give rise to the absence of the finest top-part of a graded bed. (1) The suspension can be free of finer grains. Probably a turbidity cur-

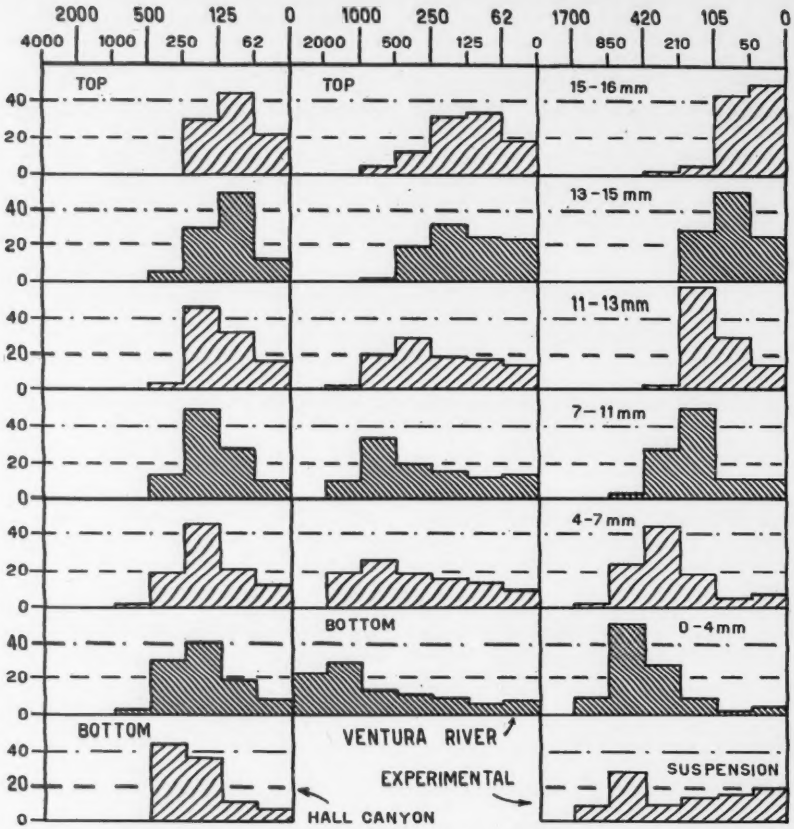

FIG. 1.—Histograms of natural graded sandstones (graywackes) from the Ventura Basin, samples roughly at equally-spaced intervals from bottom to top. Hall Canyon, bed 60 cm thick; Ventura River, bed 120 cm thick (see Natland and Kuenen, fig. 14) and experimental graded bed, 1.6 cm thick, formed by suddenly released flow (Kuenen and Migliorini, fig. 5, no. 1).

rent lacking lutite cannot travel far except on a steep slope and generally lutite will be present from the start or will be eroded by the flow on its way down. (2) On a slope the turbidity current may retain sufficient velocity, even at its dilute rear end to carry the finest grades away. (3) Normal marine currents may prevent deposition of lutite even on a horizontal floor. (4) The following turbidity current may also sweep away the upper film of a graded deposit. This will occur most readily on a slope, where the current tends to have eroding power, or on the first part of the horizontal floor beyond, before the current has become completely adjusted and lost its eroding power.

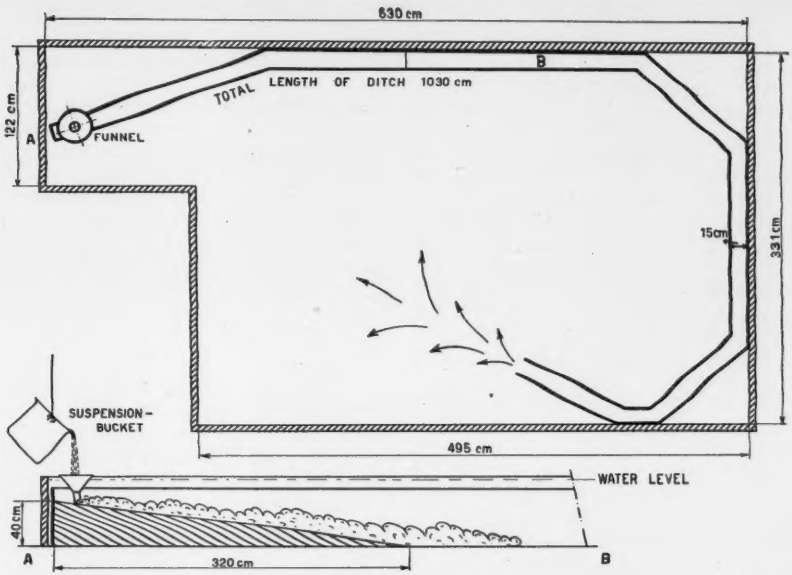

FIG. 2.—The subaqueous channel ending in a wide tank used in the present experiments.

EXPERIMENTAL INVESTIGATIONS

In the senior writer's former experiments on turbidity currents of high density the suspension was provided at its origin in a bucket or a box and then released suddenly as a whole. This arrangement was intended to imitate a natural flow starting as a slide and becoming slightly diluted as it moves down a steep slope. The deposit from such a flow was always found to grade throughout its entire thickness from coarse at the bottom to fine at the top. The histograms of figure 1 show that the experimental beds are characterized by grading which resembles to a remarkable degree that of natural graded sandstones.

In the present experiments, the currents were fed at their origin at a constant rate for periods of ¼ to 1½ minute. The suspension was poured evenly into a wide funnel fixed at the upper end of a sloping subaqueous channel (fig. 2).

The first attempts (experiment 237) were not successful because the supply was too slow (0.8 liters per second). The thin wedge of suspension slid down the slope in a non-turbulent mass. Although it moved to 8 m from the origin, that is 5 m beyond the lower end of the slope in the ditch, no truly turbulent flow was developed except for a very dilute cloud formed along the upper surface and passing on beyond to the end of the ditch. Here the cloud spread out in the wide basin and formed a thin graded lamina of silt and clay. This type of movement in a sliding wedge had already been observed in earlier experiments. It forms a transition between subaqueous mud flow and turbidity flow. It was observed to occur along the bottom of a normal turbidity current and to become incorporated in the latter further

along. The deposit tended to be irregular in thickness and to become broken apart, finally disappearing farther away. Clean graded sand occurred locally below, and everywhere above and beyond the unsorted material of the wedge.

In the lower right hand corner of figure 3 histograms are drawn showing the composition of the suspension, of the upper and lower parts of the bed 300 cm from the origin and of a sample of the entire thickness 500 cm from the origin. It will be seen that no sorting or grading has taken place. The mixture has been deposited over its entire length and thickness in precisely the same composition as provided at the start.

In the following experiment (no. 238) a wider funnel was used and the feeding thus speeded up (4.4 liters per second). True turbidity currents resulted. At the lower end of the slope the deposits tended to show a thin coarse stratum at the bottom and some grading to fine at the very top. The main mass was practically uniform. However, figure 3 demonstrates that these variations are so slight as hardly to show up in the histograms. Further along the ditch the coarse lower lamina was practically absent, but the grading towards the top was somewhat more pronounced. Still further away the grading at the top became very marked. It should be noted how well the fine mud has been washed from the sands in the turbulent flow, and that some coarse material is found even at the top of the bed.[2]

The horizontal grading is very regular, although slight, as shown by the histograms of a different bed in the upper right hand of figure 3.

These results are in striking contrast with those of earlier experiments briefly described above. The suddenly released flows deposited beds grading from coarse to fine all the way up from the base. The constantly fed flows tended to form beds without any grading until the supply stopped and a normal graded top was built onto the non-graded foundation. The relative thickness of the non-graded part of the bed depends on the time occupied by the feeding as compared to the time occupied by the tail in passing with its gradually slackening flow and decreasing sedimentary load. The farther from the origin the longer the latter process lasts and the more important the graded upper part becomes.

[2] The analyses slightly over-emphasize this feature, however, because some of the coarse grains are actually agglomerations of finer grains, due to insufficient dispersion.

STRUCTURAL DEFORMATIONS

Some of the experimental beds previously described (Kuenen and Migliorini, 1950) showed contemporaneous deformations, recalling those frequently observed in natural graded beds. Besides rather irregular contortions formed close to the origin and a complicated structure developed in the distal silt and clay deposits, one steep anticlinal fold of the four lower beds was discovered several meters from the origin (fig. 4; from Kuenen and Migliorini, 1950, pl. 3, fig. A). The fold was attributed to the drag exerted by the next turbidity current because the slope at that spot was practically nil.

However, it was later discovered (by removing the lower bed in a large sample taken just beyond the lower end of the slope in the ditch) that the following bed extended downwards in irregular pockets as if fingers had been pressed into the bed below, and that the lower bed extended upwards at one spot in a wedge-shaped intrusion into the base of the covering bed (Natland and Kuenen, 1951). It therefore appears more probable that the deformations in the experimental beds are mainly due to the sudden deposition of overburden on a highly mobile substratum.

In the present experiments somewhat different types of deformation were observed. The upper, watery film of clay and silt of one of the beds has been locally stripped off, and forms streaks

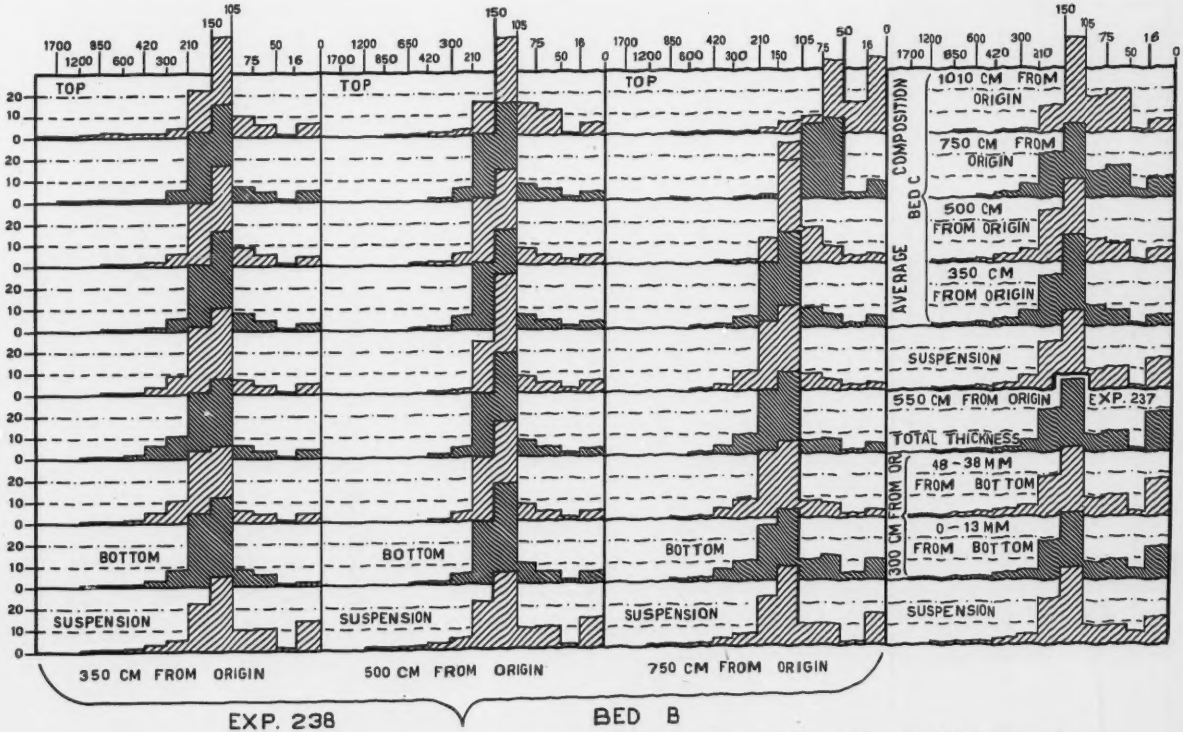

FIG. 3.—Histograms of experimental beds formed by constantly fed flows. Experiment 238, true turbidity currents. Experiment 237 a wedge-shaped, non-turbulent flow, without grading or sorting.

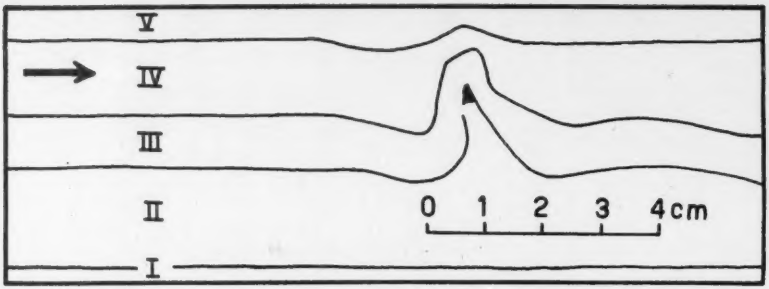

FIG. 4.—Fold-like deformation in experimental bed, probably due to sudden emplacement of overburden. Arrow shows direction of turbidity current.

passing up sharp angled wedges in the covering bed (fig. 5). The clay film of another bed wraps around ball-like portions along the base of the covering bed or even towards the center, and the sandy part of the lower bed has in some cases flowed up between the roundings of these balls (fig. 6).

Evidently two factors play a part in the forming the structures of the experimental beds: (1) drag exerted by the turbidity current on the watery clay film of its bed, (2) local settling and squeezing caused by the rapid accumulation of overburden on the highly mobile foundation.

In natural graded graywackes, pockets and less regular local deformations due to overburden have been discovered. Also known are true slump structures

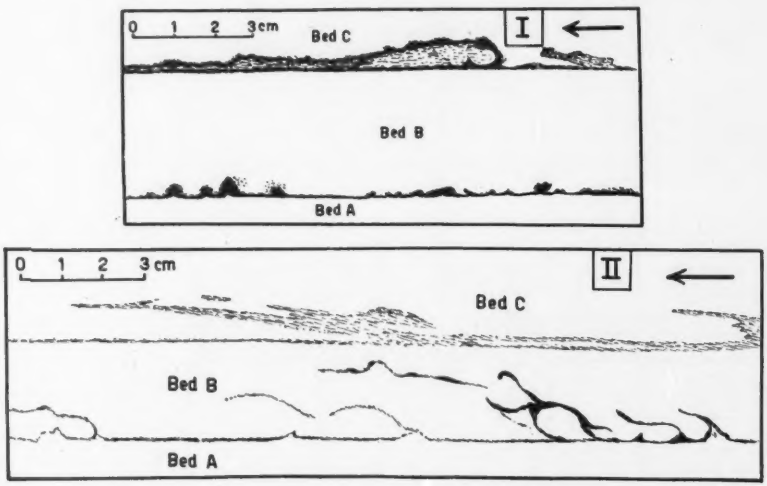

FIG. 5.—Structures in beds (experiment 238) due to stripping off of watery clay and silt of bed B by following current which deposited bed C. Ball-like structures in bed B. Section I = 500 cm, section II = 525 cm from origin.

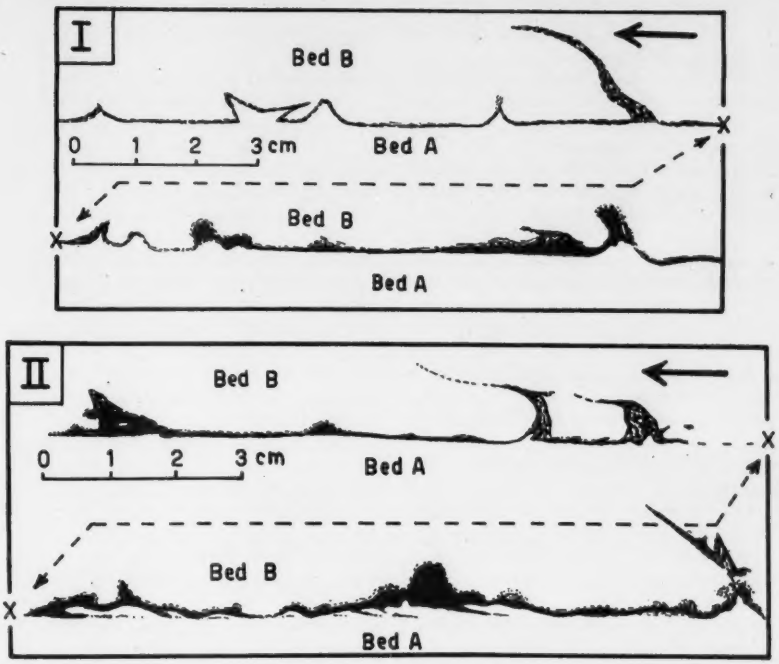

FIG. 6.—Structures in contact of beds (A and B) (experiment 238). Section I = 500 cm from origin, section II = 400 cm from origin.

and a curious deformation termed "crinkled bedding" by Migliorini (Migliorini, 1950, Natland and Kuenen, 1951). The origin of the latter is not yet clearly understood but it may be related to the ball-like formations of the present experiments.

EXPLANATION OF STRUCTURES AND ABNORMAL TYPES OF GRADED BEDDING

Considering the several mechanisms by which graded deposits can be formed, such as decreasing competence of currents, volcanic eruptions, sand storms, wave turbulence, and turbidity currents, the wonder is that more bedding is not graded. Whether a bed is deposited from suspension or due to decreasing competence, it should be graded. Two possible reasons, uniformity of source material or the thinness of each graded series composing an apparently uniform bed, will be treated below. Grading may be destroyed by the reworking action of macroorganisms, but the bedding would also be destroyed unless reworking were restricted to mixing of the upper part of each graded bed (Bramlette and Bradley, 1942).

Perhaps on the one hand many sandstones are cross-bedded without this structure being apparent, while on the other hand grading may prove more common if greater attention is given to textural details in the field.

The analysis of settling given in a former paragraph and in the experiments can serve as a basis for an attempt to

explain the development of abnormal types of graded bedding and of structural deformations.

The few available mechanical analyses and the majority of published descriptions of graded sandstones, especially the graded graywackes, fit the theoretical deductions and experimental results perfectly, if it is assumed that the turbidity currents started suddenly.

In the Ventura Basin there is evidence of an appreciable slope of the sea floor. It is therefore not surprising to find that the upper part of many graded sandstones is missing. Both transport by the turbidity current itself of the finest grades away down the slope and erosion by the following current can have played a part. The same applies to the ultra-proximal parts of glacial varves deposited on the subaqueous delta at the mouths of ice tunnels

The frequent abrupt reversions to coarse texture observed both in the Ventura Basin and in proximal varves can be accounted for satisfactorily by assuming pulsations in the supply. Variations in the rate of melting are to be expected during the summer and these may mark a daily rhythm or longer, more arbitrary changes.

A slide on a sloping sea floor may easily trigger off another slip so that the first turbidity current will be followed by a second one at so short an interval that sedimentation from the first has not finished or has even barely started before the other one arrives. Generally the latter will be more dense at its head than the tail of the former, otherwise it would lag behind. Hence it dives under the dilute tail and starts to build up its own graded bed with a coarse base resting on the finer material of the interrupted bed. The separation of a single turbidity current into two or more such currents (Menard and Ludwick, 1951) might produce similar interrupted graded bedding.

Some deep-sea core samples contain beds showing a wide range of grain sizes up to fine gravel but with no grading or sorting. These layers were evidently deposited by normal subaqueous mud flows or by the non-turbulent wedge-shaped flows described above.

Other deep-sea sands are doubtless due to volcanic eruptions. They should consist of volcanic material, mainly ash. The grading and sorting will depend, besides, on the size frequency distribution of the particles, on the depth, and on duration of the eruption. In shallow water an eruption which does not throw the volcanic cloud to great heights and which provides constant material for a long period, will produce a poorly sorted bed with no grading except towards the top. The deeper the water, the higher the eruption cloud rises, and the shorter the paroxysm lasts the more pronounced will be grading and sorting of the resulting deep-sea deposit. If the duration of the eruption is short compared to the time the largest particles require to reach the sea floor the grading and sorting will be perfect. Strong winds will carry away finer ash particles and marine currents will act likewise. In both cases the top of the volcanic bed may be relatively coarse.

Fabric analysis may be capable of separating graded bedding caused by pure settling from graded bedding deposited by a current. Dapples and Rominger (1945) found that grains on bedding planes of current-deposited sand had a statistically significant orientation with the long axes parallel to the direction of flow. In contrast, grains deposited by pure settling should have a random orientation in a bedding plane.

The difference between a volcanic deep-sea sand deposited from a turbidity current and one formed directly from an eruption should be that the latter may show better grading and especially better sorting in each level and random orientation of grains, while the former will tend to contain more foreign material such as clay, organic tests, terrigenous sand grains, or glauconite, and grains will tend to be parallel to the current movement. Detailed

microscopic examination and grain size analyses of a few separate samples taken at various levels throughout a graded core should enable an investigator to decide in most cases which of the two causes mentioned is responsible for the deposition of the graded bed.

Deposits of wind borne material on the sea floor will resemble in many respects volcanic deep-sea sands, but there are some important differences. Apart from the different nature of the grains they will seldom exceed the fine sand grade. Hence the duration of the sand storm will be short compared to the time of settling, resulting in good sorting and marked grading. On the other hand the restricted range of sizes may limit grading, and the amount supplied by a single storm may be so small that it will hardly show up as a separate lamina. If the thickness drops to the same order of magnitude as the diameter of the largest grains no grading or sorting can result. Currents encountered on the way down to the sea floor will tend to scatter the fine material over wide areas and to interfere with the sorting during settling. In deep-sea regions affected by sand storms core samples therefore contain a high percentage of wind borne material without showing clear graded beds. However, microscopic examination of slides prepared from such samples may yet reveal minute graded laminae between normal pelagic material.

Storm waves are known to raise large quantities of sand even in water of a few dozen meters depth. Frequently strong currents will accompany such wave action. As these disturbances tend to diminish gradually the sediment will be deposited in a graded bed resembling the deposit of a turbidity current. A difference from the deposit of a turbidity current may be the association of a graded storm deposit with ripple marking. Moreover, fine material is more likely to be absent, and the environment must be shallow.

Many deep-sea sands show excellent grading of the type formed by turbidity currents. Phleger (1951) has shown that shallow water foraminifera and other features strongly support the hypothesis that the majority of the deep sea sands in the San Diego Trough off southern California were carried from the coast down into the trough by turbidity currents. However, there are also a number of deep-sea sands in this trough and elsewhere in the oceans which resemble the graded sands in all respects except for the grading. Although careful mechanical analyses may yet show some or all of these to possess slight grading, they cannot be explained in the same manner as the well graded beds.

Two explanations can be offered; (1) perfect sorting of the supply or (2) a current of long duration. If a highly sorted sand, such as may occur along the shore, were to form a turbidity current, it might erode only silt and clay on the downward slope. The small amount of grains appreciably larger than the median would be deposited over a short distance beyond the slope. Further along only one grain size of sand is then available for sedimentation and a non-graded bed would result, except for the upper film of silt and clay. The latter might be inconspicuous and merge with the normal deposits covering the deep-sea sand.

The experiments described above sufficiently illustrate that a current which is fed for some time at a constant rate tends to form a non-graded deposit. However, they also show that at greater distances from the origin the relative importance of the graded top part increases. This is due to the fact that the flow gradually slackens as it moves along the horizontal floor. The feeding therefore takes up a shorter part of the time occupied by the whole phenomenon when a point is considered farther away from the origin.

Another factor in the experiments was that after the flow had ceased a turbid cloud remained standing in the ditch and tank from which fine sediment settled before the next flow was sent along. This cloud was more dense

towards the far end and therefore produced a thicker upper lamina. Moreover, erosion by the following current decreased in intensity away from the origin. In nature the same factors may have operated, but if there was no confining channel and if the sea basin was large they can have had little influence.

Before considering how, in nature, a turbidity current could be fed at a constant rate, the non-graded macigno sandstones will first be discussed. As pointed above, the lower part of some thicker beds is not graded. The explanation by better sorting of the source material is hardly satisfactory in this case, because nothing points to a different source.

The suggestion has been made to the senior writer that until the coarser grains have had time to settle from the surface of the flow no grading can be produced. It was pointed out above that in a standing cloud with uniformly distributed sediment this process is in operation. But it cannot give a satisfactory explanation of the non-graded macigno sandstones. The non-graded part of the bed is much too thick and would require a suspended sediment with a very substantial part in the coarsest grade.

However, the main reason for discarding the above suggestion is that the material present in any vertical section through a graded bed has not been deposited from a vertical column through the turbidity current, as it would have been if dropped from a stationary cloud. It results from deposition as the entire length of the flow passed by. For this reason it reflects not only change in the current during the time occupied by sedimentation at this spot, but mainly the changing sedimentation from the nose to the tail of the flow. A pure reflection of the changes in a certain part of the current with time is to be found along a horizontal line in the deposit in the direction of flow. For instance, the changing conditions in the nose are traceable along the bottom of the bed.

The explanation of the non-graded part of some macigno sandstones and of non-graded (yet sorted) deep-sea sands must be sought not in unchanging sedimentation over a period of time, because this would result in horizontal uniformity at the bottom of the bed, but in a current which from the nose backwards showed uniform composition, while the upper, graded part of such a macigno bed has been deposited by the more dilute tail.

The question should be answered why some turbidity currents in nature resemble the suddenly released experimental flows while others are of the nature of constantly fed currents. If a river in flood or a storm churning up sediment in shallow water forms the source, and part of the sedimentary load is taken up on the way down, then constantly fed currents could result. A more plausible explanation, however, is by slumping. A slide of small extent measured up and down the slope would change to a current of the "sudden" type and form a normal graded bed. A slide starting over a broad area measured up and down the slope might develop into a turbidity current with uniform frontal part. As the latter type of slide should tend to set a larger volume of suspension in motion without giving it a higher velocity, it is but natural that beds with non-graded lower parts are usually the larger ones of a series.

CONCLUSIONS

Graded sandy deposits formed at depths beyond the reach of wave action or normal currents may be due to sand storms, volcanic eruptions or turbidity currents.

Sand storms and volcanic eruptions should tend to produce beds which are graded and which are also well sorted in each successive horizon. The deeper the water and the shorter the supply lasted, the more perfect should be the

grading and sorting. But normal currents and burrowing organisms tend to impair or even destroy the grading and sorting, the more so the finer the sediment and the slower the accumulation. The supply from a single sand storm may be so small that separate laminae are not visible. If the thickness drops to the same order of magnitude as the diameter of the largest grains no grading or sorting can develop. In the absence of currents, grains should show no significant orientation in a bedding plane.

The nature of the materials ordinarily should provide characteristic features to distinguish between volcanic and wind action.

Turbidity currents should form excellently graded beds in which sorting is less well developed. Grains in a bedding plane should have a statistically significant orientation parallel to the current direction. Where the grain size reverts to coarse within a deep-sea sand the arrival of a following turbidity current may be assumed. The absence of a fine-grained upper part may be explained in the same manner, or by erosion due to the following current, or to the bottom slope. The non-graded lower part of some beds is most readily accounted for by a turbidity current of uniform composition in the frontal portions. This type of current could be generated by a slide starting over a broad area measured up and down the slope. Excellent sorting of the supply (sand of one grade combined with lutite) may result in a deep-sea sand with no visible grading. Submarine slides without turbidity flow should form non-graded deep sea sands with very poor sorting. Contemporaneous deformations in graded graywackes and deep sea sands may be due to slumping, drag exerted by the following current, or sudden placement of overburden on very mobile deposits; some structures (Migliorini's "crinkled bedding") are still unexplained.

Graded sands deposited by storm waves should in general be associated with ripple marks and show excellent sorting at any level in a graded bed. The shallow environments should find confirmation in other features. Sands deposited by swift normal currents should be characterized by good sorting, especially if a separate lamina is examined. Grading should be arbitrary. Shallow water features should be present.

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PLATES 1–7, FIGS. 1–6, JUNE, 1952

SUBMARINE GEOLOGY OF CORTES AND TANNER BANKS[1]

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ABSTRACT

Cortes and Tanner Banks are 90 nautical miles west of San Diego, California in a marine basin-range province, designated the "Continental Borderland." The two banks and the shallow saddle-like depression which separates them have an area of 230 square miles. Contours drawn at 10 fathom intervals reveal an extensive terrace at a depth of 40 to 60 fathoms on both banks.

Sixty-six bottom samples obtained from the region permitted detailed studies of the rock and recent sediments. Only sedimentary and igneous rocks of Miocene age were found. The characteristics of the recent sediments are controlled by topography, current activity, and depth of water. An area of non-deposition or unconformity exists at the top of the banks.

INTRODUCTION

Geologic studies of continental shelf areas are of two general types. The first is an investigation of physiography, structure, and lithology in an effort to extend land geology. The second is a study of marine environments and recent sediment patterns: thus affording a key to the interpretation of ancient sediments. This report is concerned with both lines of endeavor.

Previous studies which offer regional descriptions of continental shelf areas (Sverdrup, Johnson, Fleming, 1938; Revelle and Shepard, 1939; Shepard, 1939; Shepard and Emery, 1941; Emery and Shepard, 1945) include general discussions of bank areas and their environments, but only a few investigations have been devoted specifically to banks. A report by Cayeaux (1934) deals specifically with a bank area, but is primarily concerned with the origin of authigenic materials that are characteristic of marine areas of non-deposition of clastic sediments. Several banks have been described from the area surrounding Japan (Niino, 1948), but these are very near shore, and represent a direct extension of land geology. In his discussion of the submarine geology of Ranger Bank, Mexico, Emery (1948) offers one of the few reports which deals with a marine bank as a unit.

Bank areas are of particular interest in that they may represent the early stage in the development of "buried hill" structures. By establishing the character and environment of present day sedimentation, ancient sediments of such structures may be more readily interpreted. Two banks, Cortes and Tanner, located off southern California at the southeast terminus of the Santa Rosa-Cortes Ridge were selected for study.

Cortes and Tanner Banks are 90 nautical miles west of San Diego, California in the region included by Latitude 32° 20′ N., Latitude 32° 50′ N., and longitude 119° 30′ W., Longitude 118° 50′ W. (pl. 1). The two banks and the intervening saddle-like depression have an area of 230 square miles if the lower limit of the area be set at the 150 fathom contour.

Two sampling expeditions abroad the "Velero IV" were conducted to the region, in May and August of 1949. These trips yielded 50 bottom samples. Eight additional samples were secured from the Hancock collection; and these were later augmented by eight others from the Navy Electronics Laboratory of San Diego, California. Table 1 gives sample locations and general information, while plate 2 shows the positions of sampling

[1] Contribution of Allan Hancock Foundation No. 89.

stations, and the nature of the devices used.

The writer is indebted to Dr. K. O. Emery who suggested this study, and offered invaluable criticism and encouragement: and to the Allan Hancock Foundation of the University of Southern California for the use of the laboratory and ship-board facilities.

GEOLOGIC ENVIRONMENT

Cortes and Tanner Banks are located in a basin-range province between the narrow continental shelf and the continental slope of southern California. Shepard and Emery (1941) suggested that this province be referred to as the continental borderland.

The physiography of the borderland is controlled by faulting which occurred in the late Miocene (Emery and Shepard, 1945), and exhibits a northwest-southeast trend, paralleling the structural trend of southern California. In the northern portion of the borderland, there is a counter east-west trend whose prime expression is the Channel Islands. This transverse element is an extension of the transverse ranges found on shore (Reed, 1933).

The area is characterized by a series of deep basins and intervening ridges. The basins have a maximum depth of 1080 fathoms and are present-day areas of sediment accumulation. The ridges, which are often expressed as islands or banks, rise from the basin areas with exceptionally steep slopes. These topographic highs are areas of sediment bypassing (Revelle and Shepard, 1939).

Miocene sedimentary and volcanic rocks are the predominant lithologic types cropping out in the borderland (Emery and Shepard, 1945). Some metamorphic rock has been reported and is considered to be Franciscan (Jurassic?). No Pliocene or Pleistocene rock is known to crop out in the region.

OCEANOGRAPHY

Because no oceanographic data were collected during the course of this investigation, a report by Sverdrup and Fleming (1941) is used as a basis for the following discussion of the oceanographic conditions existing in the Cortes and Tanner Banks area. They report two surface currents in the region. A southeasterly current with a velocity of 15 to 20 cm./sec. flows on the west side of Santa Rosa-Cortes Ridge, whereas the northwesterly Southern California Counter Current with a velocity of 10 to 15 cm./sec. is generally active on the east side of the ridge. Much turbulence occurs at the interface of these two opposing currents. This is evidenced by a thickening of the convection layer from 5 fathoms near shore to 75 fathoms in the Cortes and Tanner Banks area.

The probable lower limit of strong current movement at 108 fathoms (200 meters) results from the topographic control exercised by the Santa Rosa-Cortes Ridge. At this depth, current activity consists of a north-northwest Coastal Deep Current with a velocity of 10 cm./sec., which is present from the shore to the outer edge of the Santa Rosa-Cortes Ridge. Seaward from the ridge, the deep southeast California Current is encountered.

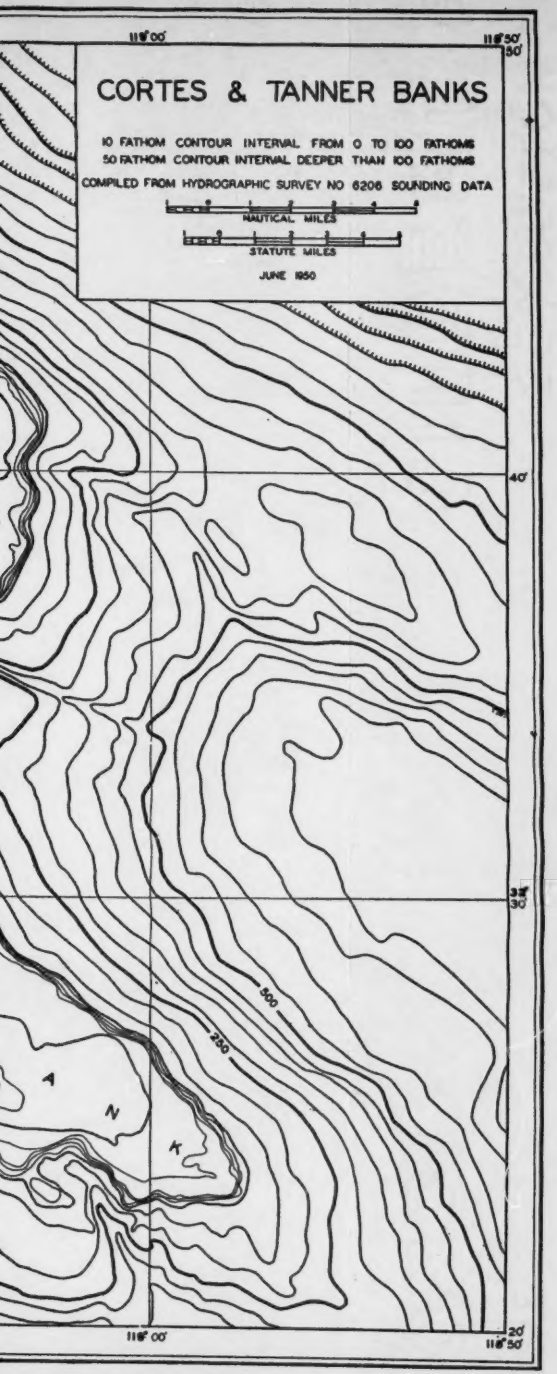
Throughout the region, surface waters are saturated with oxygen, but below the zone of photosynthetic activity the oxygen content rapidly decreases.

In summary, the banks are in a region of shifting and conflicting currents that give rise to much turbulence. This turbulence may be significant in maintaining and placing fine materials in suspension, thereby rendering them susceptible to transport by weak currents. However, in an area of shifting currents the net sediment transport is radially downslope (Sverdrup *et al.* 1942), so that little reflection of current directions may be expected in the sedimentation patterns of the bank tops.

PHYSIOGRAPHY

Cortes and Tanner Banks are at the southeast end of the northwest-southeast trending, Santa Rosa-Cortes Ridge.

PLATE 1.—Chart of Cortes and Tanner Banks with inset showing relation to Cal



on to California coast.

TABLE I.—*General description of samples*

Sta no.	Field no.	Latitude North	Longitude West	Depth Fathoms	Device[1]	Bottom Notation
1	1340-41	32-41.0	119-06.0	26	Drg	Sand-Rock
2	1348-41	43.0	11.7	46	Drg	Rock
3	1330-41	29.8	05.0	100	Drg	Sand
		29.7	04.5			
4	1335-41	25.8	07.5	52	Drg	Sand
		25.5	08.0			
5	1341-41	30.8	09.5	127	Drg	Sand-Rock
		30.5	09.5			
6	1342-41	33.3	15.3	40	Drg	Sand-Rock
7	1343-41	35.0	11.8	105	Drg	Sand-Rock
		35.0	11.9			
8	1346-41	36.5	20.0	75	Drg	Rock
9	N-643	23.0	118-58.0	56	Snp	Sand
10	N-644	23.4	119-00.0	60	Drg	Sand-Rock
11	N-756	28.5	09.0	45	Snp	Sand
12	N-671	42.0	08.0	29	Snp	Sand
13	N-672	42.3	06.8	42	Snp	Rock
14	N-753	42.2	11.8	52	Snp	Sand
15	N-754	43.0	10.0	35	Snp	Rock
16	N-755	42.5	10.0	32	Snp	Sand
17	1822-49	27.6	02.0	100	Snp	Sand
18	1823-49	25.3	118-58.7	99	Snp	Sand
19	1824-49	23.3	119-02.6	98	Snp	Sand
20	1825-49	24.5	05.2	63	Snp	Sand
21	1826-49	26.2	03.5	46	Snp	Sand
22	1827-49	26.7	03.7	53	Snp	Sand
23	1828-49	27.7	04.5	50	Snp	Sand
24	1829-49	30.8	06.5	95	Snp	Sand
25	1830-49	26.3	12.0	75	Snp	Sand-Rock
26	1831-49	29.9	15.2	82	Snp	Sand
27	1832-49	31.4	14.5	48	Snp	Sand-Rock
28	1833-49	33.5	12.3	56	Snp	Sand
29	1834-49	35.4	09.7	136	Snp	Sand
30	1835-49	36.1	08.8	86	Snp	Sand-Rock
31	1836-49	32-37.2	119-07.3	150	Snp	Sand
32	1837-49	38.5	05.9	51	Snp	Sand
33	1838-49	40.9	02.8	108	Snp	Sand
34	1839-49	40.8	05.6	28	Snp	Sand
35	1841-49	41.1	07.5	42	Snp	Sand
36	1842-49	41.1	07.8	42	Snp	Sand
37	1843-49	41.2	10.3	55	Snp	Sand
38	1844-49	42.5	08.7	36	Snp	Sand
39	1845-49	43.8	07.2	115	Snp	Sand
40	1872-49	42.3	14.8	300	Snp	Sand-Rock
41	1873-49	40.4	15.7	80	Snp	Sand-Rock
42	1874-49	28.3	16.8	130	Snp	Sand
43	1875-49	36.9	17.8	90	Snp	Sand
44	1876-49	35.1	17.9	58	Snp	Sand-Rock
45	1877-49	33.3	19.9	66	Snp	Sand
46	1878-49	31.6	20.7	89	Snp	Sand
47	1879-49	30.5	18.5	85	Snp	Rock
48	1880-49	32.2	16.9	45	Snp	Sand
49	1881-49	34.1	15.6	45	Snp	Rock
50	1882-49	33.8	15.3	42	Drg	Rock
		33.4	15.2			
51	1883-49	30.3	13.4	47	Snp	Sand
52	1884-49	29.2	12.6	26	Drg	Rock
		28.6	12.3			

TABLE I.—*continued*

Sta no.	Field no.	Latitude North	Longitude West	Depth Fathoms	Device[1]	Bottom Notation
53	1885-40	29.2	12.6	24	Drg	Rock
		28.6	12.3			
54	1886-49	29.2	12.6	24	Drg	Rock
		28.6	12.3			
55	1887-49	28.1	10.7	38	Snp	Sand
56	1888-49	27.6	09.3	31	Snp	Rock
57	1889-49	27.1	08.1	20	Drg	Rock
		26.8	07.8			
58	1890-49	26.8	07.8	18	Drg	Rock
		26.5	07.7			
59	1891-49	32.4	11.8	60	Snp	Sand
60	1892-49	34.3	10.9	85	Snp	Sand
61	1893-49	32-35.3	119-10.6	128	Drg	Snad
		35.7	10.4			
62	1894-49	40.8	07.3	42	Snp	Sand-Rock
63	1895-49	41.5	07.6	22	Snp	Sand
64	1896-49	42.2	07.6	30	Drg	Rock
		42.6	07.5			
65	1897-49	42.8	07.6	39	Snp	Sand-Rock
66	1898-49	43.6	07.8	40	Drg	Rock
		43.6	07.8			

[1] Sampling device; Drg. = dredge, Snp. = snapper.

The sides of the banks are steep, with an average slope of 6 degrees. These steep slopes rise 850 to 1080 fathoms above the floor of the basins that flank the banks on three sides.

Tanner Bank, the northernmost of the two, has an area of about 58 square miles, and a minimum depth of 12 fathoms; Cortes Bank is 120 square miles in area, with a minimum depth of 2 fathoms. The saddle, separating the banks, has an area of 50 square miles, and an average depth of 120 fathoms.

The most striking physiographic feature of the area is the extensive terrace on each bank at a depth of 40 to 60 fathoms (pl. 1). Rising above this terraced surface are three major topographic highs, one on Tanner Bank and two on Cortes. Sampling shows that these consist of basaltic rock, whereas the terrace is of sedimentary rock. Possibly the terraced areas resulted from wave erosion at a time when sea level was at a relatively lower stand, and the highs of volcanic material are merely a manifestation of their greater resistance to wave erosion. The depth of the terrace surface corresponds with the values generally accepted for the lowering of sea level during the Pleistocene Glacial epoch.

Two narrow canyons cut the saddle region immediately south of Tanner Bank (pl. 1). The axes of these canyons are in a straight line paralleling the general trend of the ridge. One deepens to the northwest and presents an asymmetrical cross section; the other is symmetrical, and deepens to the southeast. The alignment of the axes of these canyons, and their parallelism to the structural trend of the regions suggests that they are of fault origin.

LITHOLOGY

Rock was obtained at 27 sample locations. The majority of these were dredgings, but occasionally the bottom snapper recovered small rocks. A total of 765 pieces of rock were secured in the course of the sampling program. Of these, 125 fragments are considered representative of the rock cropping out. The criteria for distinguishing between rock representative of the outcropping material from that which has been trans-

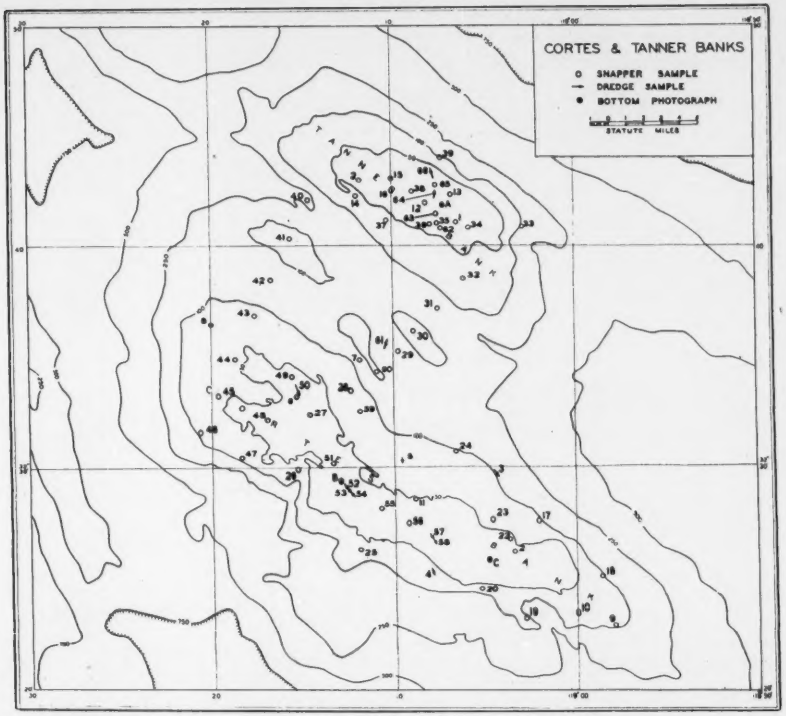


PLATE 2.—Locations of samples and bottom photographs.

ported have been given by Emery and Shepard (1945).

Preliminary studies of the lithologic materials were conducted on board ship immediately after the sample was recovered. The size, shape, rock type, and evidence of being representative of rock in situ, was recorded for each specimen. Representative samples of each lithologic type were selected for laboratory study, after which the bulk of the sample was discarded. This procedure eliminated the need to return large volumes of rock to the laboratory.

The detailed description and classification of the rock specimens were conducted in the laboratory (table II). Thin-sections of the igneous rock were prepared and studied. The sedimentary rocks were examined with the aid of a binocular microscope and hand-lens. In many cases, where the sedimentary material appeared highly calcareous, it was necessary to determine the percentage of calcium carbonate in order to classify the rock correctly. This was done by digesting the rock in dilute hydrochloric acid and calculating the percentage of calcium carbonate from the weight loss.

Only igneous and sedimentary rocks were found in the bank area. Of the rock specimens, 67.1 per cent are igneous rocks, primarily of volcanic origin. Sedimentary rock constitutes the remaining 32.9 per cent; authigenic phosphorite is the major rock type of the sedimentary suite.

TABLE II.—*Lithology*

Station no.	Rock Type	Number of Pieces	Roundness
1	Phosphorite	1	SR
	Basalt porphyry	2	A-SA
2	Rudaceous limestone	1	R-SR
	Calcareous medium sandstone	3	R-SR
5	Arenaceous limestone	1	SR
	Calcareous fine sandstone	1	R-SR
6	Biotite granodiorite	1	R
	Basalt porphyry	3	SA-SR
	Hornblende biotite dacite porphyry	1	SR
8	Basalt porphyry	7	SA-SR
10	Black argillaceous limestone	1	SR
	Phosphorite	6	SR
	Foraminiferal limestone	1	A-SA
13	Basalt porphyry	26	A-SR
15	Basalt porphyry	2	A-SA
25	Phosphorite	1	SR
27	Hornblende diorite	2	SR-R
	Quartzite	1	R
	Andesite porphyry	19	SA-SR
	Basalt porphyry	3	SR
30	Basalt porphyry	4	SR
	Phosphorite	8	SR
40	Basalt porphyry	2	SA-SR
	Phosphorite	1	SR
	Argillaceous limestone	2	SA-SR
41	Phosphorite	1	SR
44	Biotite granodiorite	3	R
	Basalt porphyry	8	SA-SR
47	Argillaceous limestone	1	SR-R
50	Argillaceous limestone	27	SA
	Arenaceous limestone	110	A-SA
	Calcareous fine sandstone	14	SA-SR
	Calcareous medium sandstone	16	SA-SR
	Ferruginous coarse sandstone	1	SA
	Phosphorite	8	SR
	Basalt porphyry	283	A-SR
	Vesicular basalt vitrophyre	8	A-SA
	Hornblende diorite	1	R
52	Basalt porphyry	3	SA
53	Basalt porphyry	2	A-SA

TABLE II.—*continued*

Station no.	Rock Type	Number of Pieces	Roundness
54	Vesicular andesite porphyry	1	A-SA
	Basalt porphyry	19	SA
58	Basalt porphyry	3	A-SA
62	Calcareous medium sandstone	1	A
64	Basalt porphyry	1	A-SA
65	Phosphorite	1	SR
66	Calcareous medium sandstone	14	SA-SR
	Basalt porphyry	62	A-SA
	Phosphorite	21	SA-SR

The majority of the rock specimens are well rounded to subrounded clasts which ranged from granule to boulder size. The majority of these rounded clasts exhibit a growth of encrusting organisms on one side. This coating of organisms is indicative of long periods of stability, during which this side of the

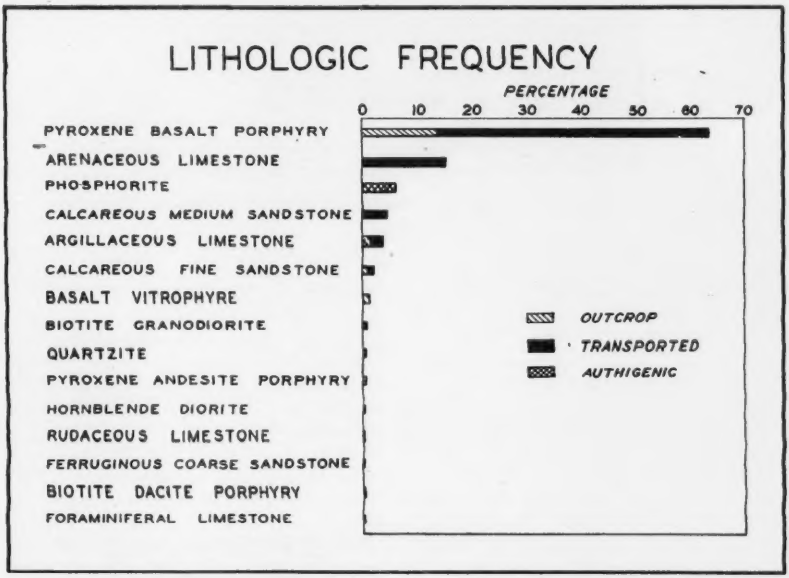


FIG. 1.—Frequency and nature of occurrence of each lithologic type.

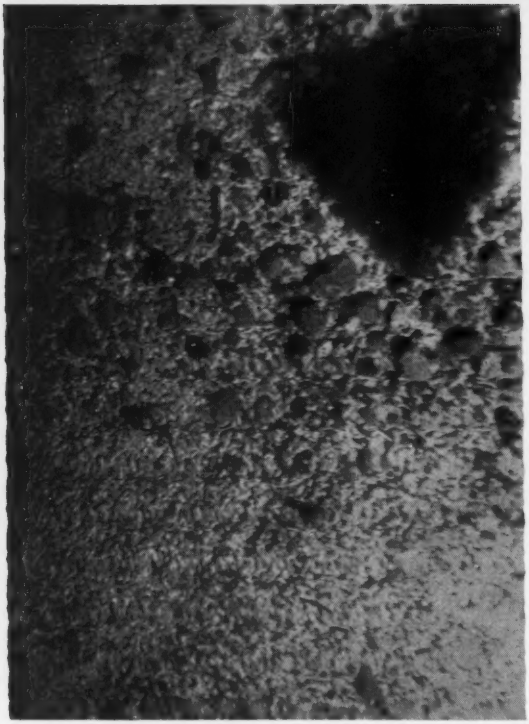


PLATE 3-1.—Bottom photograph of Cortes Bank at location "B," depth 50 fathoms.

rock was continuously exposed. Further, it indicates that sediment accumulation was not sufficient to cover the cobbles (plate 3).

Pieces of unweathered basalt porphyry with freshly fractured surfaces were recovered from dredge hauls that were characterized by sharp shocks and by great changes of tension on the dredge cable. These are considered to be indicative of rock fragments broken from bottom outcrops (plate 3). The occurrence of outcrops of rock relatively free of sediment cover, and cobbles with encrusting organisms on one side, are indicative of an area of nondeposition at the top of the banks.

The basalt porphyry, the most abundant rock in the area (fig. 1), consists of phenocrysts of labradorite (An_{60}) in a matrix of microlites of labradorite (An_{64}), and augite granules. The basalt showed several textural variations; the majority of the specimens have large plagioclase phenocrysts, in many cases 2 inches in length, in a very fine grained holocrystalline matrix (Clements, 1945). Other samples showed a diabasic or seriate texture, The minor accessory minerals are magnetite and hypersthene. Some secondary chlorite is present, which is believed to be an alteration product of the abundant pyroxenes.

The second most abundant rock in the

PLATE 3-2.—Bottom photograph of Cortes Bank at location "C," depth 25 fathoms.

area is an arenaceous limestone, It is characterized by a light buff color, a massive appearance, and consists of fine, subangular to subrounded, well sorted sand grains in a matrix of calcium carbonate. The calcium carbonate shows no organic structures and is 59.2 per cent by weight of the rock.

The other rock types and their relative frequency of occurrence are shown in figure 1. Varieties of limestone are shown to be in greater abundance than is generally found on shore. Emery and Shepard (1945) also reported a relative abundance of limestones, in contrast with the predominantly clastic nature of the sediments of shore.

Plate 4 shows the areal distribution of the rock types and denotes those deemed representative of rock in situ. The outcrops of basalt porphyry coincide with the topographic highs, whereas the sedimentary rocks crop out in the terraced areas. This distribution of rock types corroborates an earlier statement which attributes the existence of the topographic highs above the terrace surface to the processes of differential erosion.

Fossil evidence of the age of the sedimentary rocks of the area is meager. An incoherent foraminiferal limestone which contains abundant *Siphogenerina*

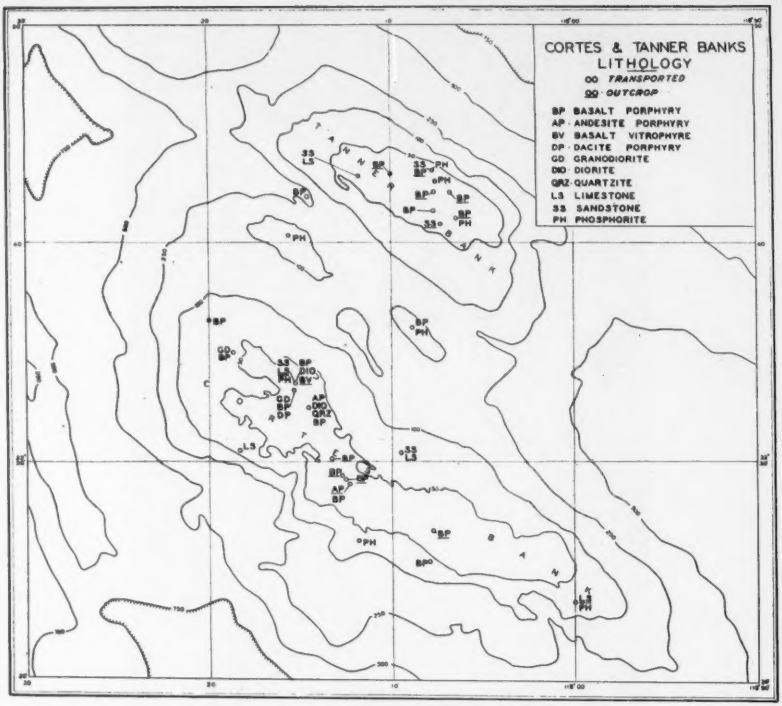


PLATE 4.—Areal distribution of lithology.

reedi, Cushman, and *Siphogenerina branneri* (Bragg) indicative of the middle Miocene was dredged from the southeast end of Cortes Bank. This is the only fossiliferous material recovered in the present investigation. Further indication of the age of the sedimentary materials of the area is the report by Emery and Shepard (1945) of a Foraminifera-bearing mudstone of middle Miocene age from the Tanner Canyon area. Tentatively therefore, the age of the sedimentary rock of the Cortes and Tanner Banks area is considered middle Miocene.

The age of the igneous material of the area is difficult to establish. Submarine geologic techniques, as yet, give no indication of the structural relationship of the volcanics and the Miocene sediments. A Miocene age, however, is given to the volcanics (Emery and Shepard, 1945), on the basis of their lithologic similarity to the abundant Miocene extrusives of the islands of the borderland and the adjacent mainland.

RECENT SEDIMENTS

Grain-Size Distribution

Mechanical analyses of the recent sediments were made by sieving, using a set of Tyler standard screen sieves having openings corresponding to Wentworth grade limits. Cumulative curves were plotted on probability paper, and the median diameter, sorting coefficient,

TABLE III.—*Parameters of the original sediment*

Station no.	Median Diameter mm.	Sorting Coefficient	Phi Skewness	Color (wet)
1	0.25	1.38	−0.075	mineral gray
3	0.81	1.75	0.11	light mineral gray
4	0.74	1.70	−0.005	mineral gray
5	0.62	1.80	−0.05	mineral gray
6	0.29	1.28	−0.015	very light mineral gray
7	0.20	1.37	−0.005	grayish olive
9	0.30	1.75	−0.25	light greenish olive
10	0.42	1.65	−0.10	mineral gray
11	0.96	1.64	0.18	light mineral gray
12	0.71	1.33	−0.02	light mineral gray
14	0.16	1.30	−0.055	mineral gray
16	0.88	1.52	0.14	light mineral gray
17	0.23	1.34	0	medium grayish olive
18	0.12	1.27	−0.01	medium grayish olive
19	0.14	1.27	0.01	medium grayish olive
20	0.14	1.27	0.005	light grayish olive
21	0.27	1.42	0.09	greenish mineral gray
22	0.27	1.35	0.02	light mineral gray
23	0.56	1.72	−0.31	mineral gray
24	0.13	1.40	−0.005	light grayish olive
25	0.18	2.20	−0.52	light grayish olive
26	0.13	1.12	−0.005	light grayish olive
27	0.82	3.53	−0.43	light greenish mineral gray
28	0.25	1.54	0	mineral gray
29	0.11	1.24	−0.02	deep olive
30	0.26	5.00	−1.55	deep olive
31	0.19	1.27	0	light olive
32	0.22	1.25	−0.005	light olive
33	0.28	1.42	−0.04	light olive
34	0.36	1.66	0.045	mineral gray
35	0.61	1.43	0.04	mineral gray
36	0.45	1.43	0	mineral gray
37	0.43	1.44	−0.025	mineral gray
38	0.49	1.20	−0.025	light mineral gray
39	0.26	1.64	−0.18	light olive
40	0.28	2.30	−0.32	deep olive
41	1.17	2.53	0.08	deep olive
42	0.30	1.41	−0.055	deep olive
43	0.21	1.50	−0.005	olive
44	0.34	2.30	−0.58	light olive
45	0.32	1.40	−0.005	deep olive
46	0.24	1.73	−0.08	olive
48	0.14	1.17	−0.005	light greenish mineral gray
51	0.28	1.79	−0.36	mineral gray
55	0.35	1.34	0	light mineral gray
60	0.85	4.60	−0.31	deep olive
61	0.10	1.30	−0.01	deep olive
62	0.50	1.35	−0.125	mineral gray
63	3.60	2.29	0.62	mineral gray
65	0.34	1.55	−0.025	mineral gray

and phi skewness of each sample was determined. The results of these analyses are listed in table III.

Median diameters ranged from 1.17 mm to 0.10 mm and averaged 0.31 mm. The average median diameter was ob-obtained from a curve (fig. 2) which is representative of the grain-size distribu-

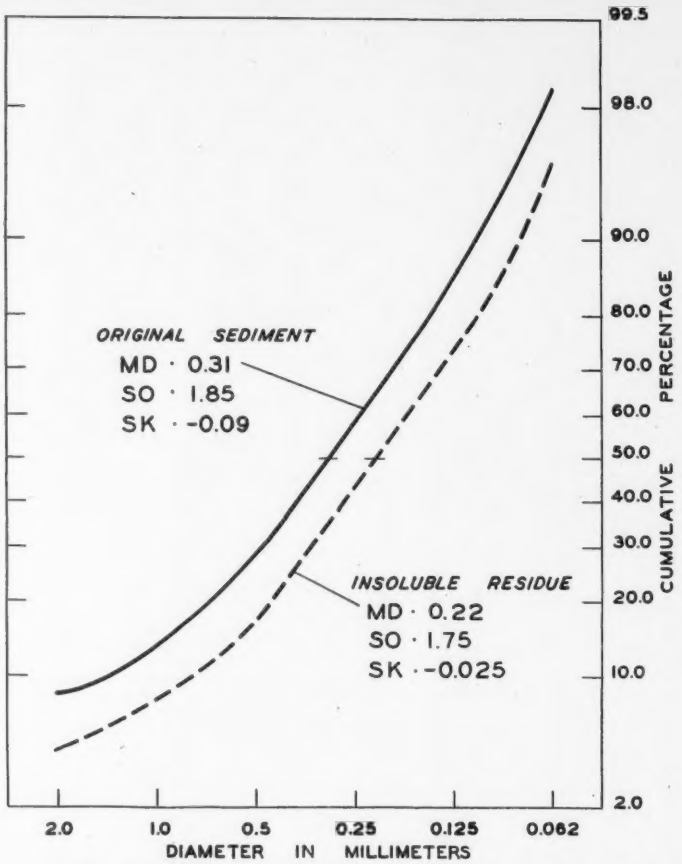


FIG. 2.—A cumulative curve of the grain size distribution of the average sediment from the area.

tion of the average sediment of Cortes and Tanner Banks. This curve was constructed from the average percentage of each size grade. Because this curve represents a composite of all the mechanical analysis data, any parameters obtained from the curve represent the average value for the sediment of the bank area.

An isopleth map was prepared to illustrate the areal distribution of the median diameters (pl. 5). This revealed a good grouping of median values, and led to the establishment of zones of grain-size distribution based on Wentworth's sand grade limits. The relationship of median grain diameters to the topography is readily seen. The tops of the banks are characterized by very coarse sand; downslope the median values decrease to very fine sand grades.

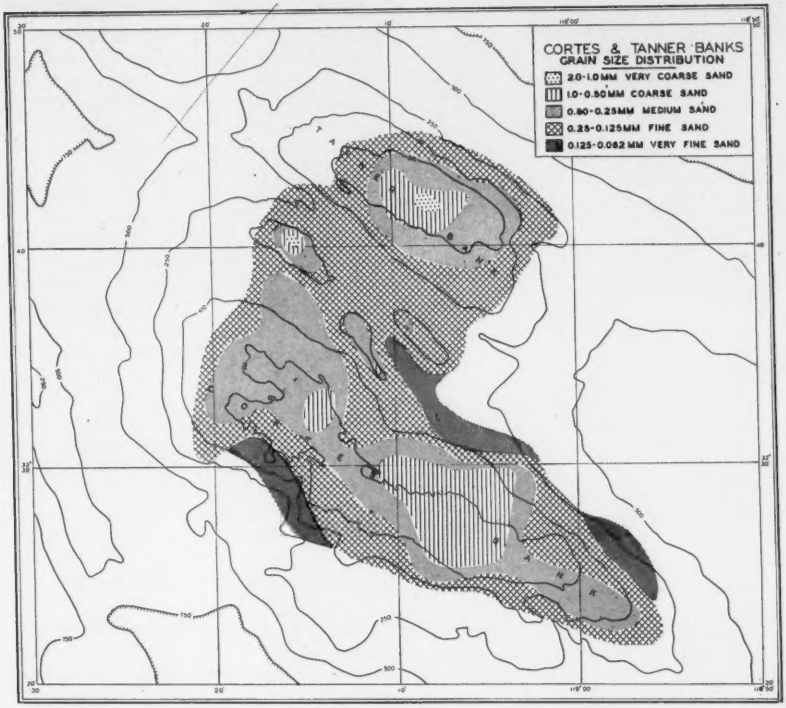


PLATE 5.—Isopleth chart of grain size distribution.

The grain-size distribution in the Tanner and Cortes Bank area is controlled by two factors; the size of the material available, and the subsequent working of the sediments by current activity.

In shoal areas which lie within the zone of photosynthetic activity, about 40 fathoms (Sverdrup, Johnson, Fleming, 1942), ample food is available to support large populations of benthonic organisms, and on the death of the organism the test is contributed to the sediment. This coarse calcareous debris is the main constituent of the coarse sand on the top of the banks. Below the euphotic zone, where there is less food, these large forms are uncommon and the prime materials contributed to the sediment are the minute tests of pelagic Foraminifera.

The great turbulence and alternating direction of current flow in the region have been discussed. This activity results in a winnowing of the fine materials from the top of the banks, yielding a lag concentration of coarse-grained elements, and a net downslope transport and accumulation of fine sediment.

The geometric sorting coefficients range from 1.17 to 5.00 and have an average value of 1.85, which was computed from the quartiles and median of the curve representative of the average sediment (fig. 2). 95 per cent of the samples have sorting coefficients of less than 2.50; thus, they are considered well sorted by the criteria established by

TABLE IV.—*Organic carbon content of recent sediments*

Sta. no.	Organic Carbon Per Cent	Sta. no.	Organic Carbon Per Cent
1	0.448	28	0.366
3	0.356	29	1.050
4	0.156	30	0.762
5	0.204	31	0.372
6	0.257	32	0.263
7	1.160	33	0.444
9	0.637	37	0.206
10	0.338	38	0.0724
11	0.179	39	0.872
16	0.775	40	1.17
17	1.150	41	1.10
18	0.785	43	1.48
19	0.556	44	0.690
20	0.415	45	1.46
21	0.250	46	0.770
24	1.000	48	0.530
26	1.190	55	0.24
27	0.489	61	1.57
		62	1.55

Trask. The sorting coefficients showed no relationship to topography or median diameters.

Values of phi skewness ranged from −1.55 to 0.62. The phi skewness of the curve of the average sediment was −0.09 (fig. 2). A total of 68 per cent of the samples were skewed toward the coarse grain sizes; 10 per cent showed no skewness; 22 per cent were skewed toward the fine grain size. This indicated that in the majority of the samples, the fine materials have been winnowed out, resulting in a curve skewed toward the coarse grain sizes. The geologic interpretations which may be derived from skewness values are rather obscure. Krumbein and Pettijohn (1938) state that skewness in many cases is merely the manifestation of the sampling error.

Organic Carbon Content

The organic carbon content of 37 sediment samples was determined by a chromic acid reduction method as described by Allison (1935). This method consists of oxidizing 0.5 gram of sediment in concentrated sulphuric acid containing an excess of potassium dichromate. The mixture is then heated to 175° C. in 90 seconds, cooled and the unused chromic acid is titrated with a standard solution 0.2 *N* ferrous ammonium sulphate, using diphenylamine as an indicator. Allison has shown that the organic carbon content determined by this method compares favorably with that obtained by other techniques. A conversion factor of 1.7 as recommended by Trask (1932) may be used to estimate the total amount of organic matter from the organic carbon content.

The organic carbon content of the sediments ranged from 0.07 per cent to 1.57 per cent with an average value of 0.64 per cent (table IV). An areal distribution chart was prepared and the organic carbon values were contoured at 0.50 per cent interval (pl. 6). Values less than 0.50 per cent are found in association with the coarse-grained materials of the bank tops. Down-slope the organic carbon content increases with a decrease in sediment grain size.

The oxygen content of the overlying water is one of the prime controlling factors of the organic carbon content of the sediment. The tops of the banks lie within the photosynthetic zone and therefore are characterized by overlying water which is saturated with oxygen. Organic material is readily destroyed in this environment. Below the zone of photosynthetic activity the oxygen content rapidly decreases and the destruction of organic matter is retarded.

The sedimentary processes of the area are also important in controlling the organic carbon content of the sediments. Organic materials are generally minute particles of low specific gravity. The turbulence and shifting current activity of the upper bank region causes the winnowing of the fine materials from the tops of the banks and their subsequent deposition downslope. This results in a depletion of organic materials at the tops of the banks and their concentration at depth with the fine sediments.

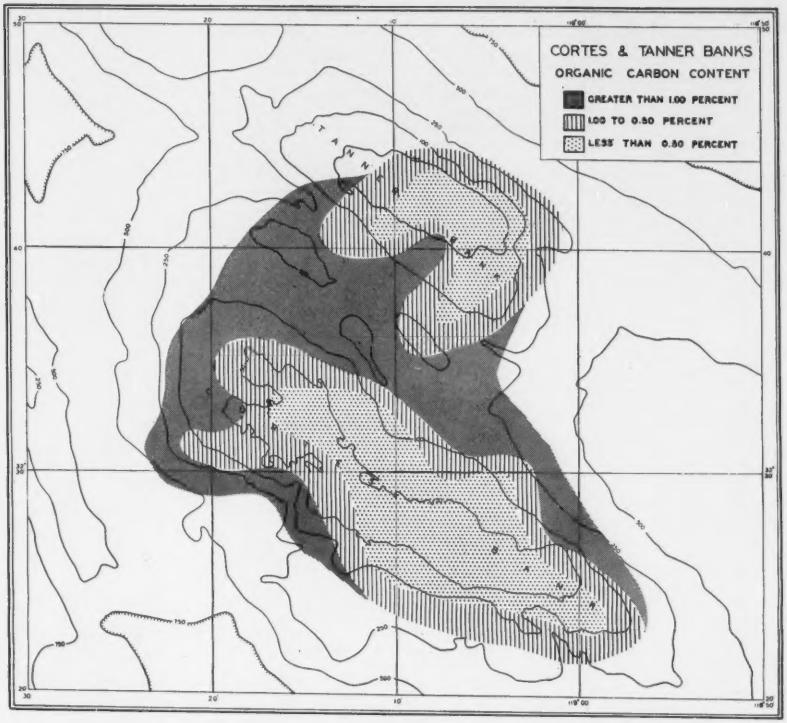


PLATE 6.—Isopleth chart of organic carbon content of recent sediments.

Calcareous and Siliceous Material of Organic Origin

Determinations were made of the percentages of shell detritus, foraminiferal tests, echinoid spines, sponge spicules, and bryozoa, composing the inert material of organic origin. The samples were examined under a binocular microscope, and the percentages were estimated to the nearest 5.0 per cent, based on mass relationship rather than on the numerical consideration of the particles of each type. The results of this study are shown in table V.

The tops of the banks are characterized by an abundance of shell debris which continues as the dominant form of calcareous material to a depth of 50 fathoms (fig. 3). This depth is significant because it closely approaches the lower limit of photosynthetic activity (Sverdrup, *et al.* 1942), thus indicating that the growth of the majority of the large benthonic organisms is restricted to regions in which the bottom lies within the euphotic zone. The supply of tests of Foraminifera above 50 fathoms is probably larger than that indicated by the low percentages, but many of these tests, because of their small mass, are winnowed out, and deposited downslope. Others probably are destroyed by solution in the acidic environment at the top of the banks, where pH values ranging from 6.6 to 6.9 were recorded from the sediment. Much of the shell debris also shows the affect

TABLE V.—*Calcareous and siliceous material of organic origin*

Sta. no.	Percentage				
	Forams.	Echinoid Spines	Sponge Spicules	Shell Detritus	Bryozoa
1	5	10	5	60	20
3	5	20	0	50	25
4	5	15	0	65	15
5	45	10	5	25	15
6	35	15	0	40	10
7	80	5	10	5	0
9	40	15	0	40	5
10	20	15	5	10	50
11	5	5	0	75	10
16	5	10	0	45	40
17	75	5	10	10	0
18	80	5	3	10	2
19	75	5	10	10	0
20	70	0	10	15	5
21	20	10	10	60	0
24	65	5	10	20	0
26	65	5	20	10	0
27	50	5	10	30	5
28	25	5	5	60	5
29	75	5	0	20	0
30	83	2	0	15	0
31	20	5	5	70	0
32	40	10	0	35	15
33	55	10	5	30	0
37	22	3	5	50	20
38	5	10	0	70	15
39	65	3	5	25	2
40	80	2	3	15	0
41	77	10	3	10	0
43	70	15	0	15	0
44	50	10	0	35	5
45	70	0	5	25	0
46	75	3	2	20	0
48	80	3	12	5	0
55	5	5	5	75	10
61	90	0	5	5	0
62	5	10	0	70	15

of the solvent action incurred by the acidic environment.

Below 50 fathoms tests of Foraminifera are the predominant form of calcareous material. Many of these tests probably have been swept downslope by current activity. The majority, however, represent the normal production of benthonic and pelagic Foraminifera in the region.

The percentages of echinoid spines, bryozoa, and sponge spicules showed no relationship to depth of water or to the sedimentation pattern of the area.

The foraminiferal fauna of the Cortes and Tanner area was studied by J. F. Riccio (unpublished report). He states that the fauna is of Recent age and coincides with the faunal assemblages of Natland's zones, III and IV. The actual depth and temperature of the samples lie within the depth and temperature boundaries of these zones.

Insoluble Residue

The calcareous material of the sediment was removed by digestion in dilute hydrochloric acid, and the percentage of insoluble residue was determined by weight loss (table VI).

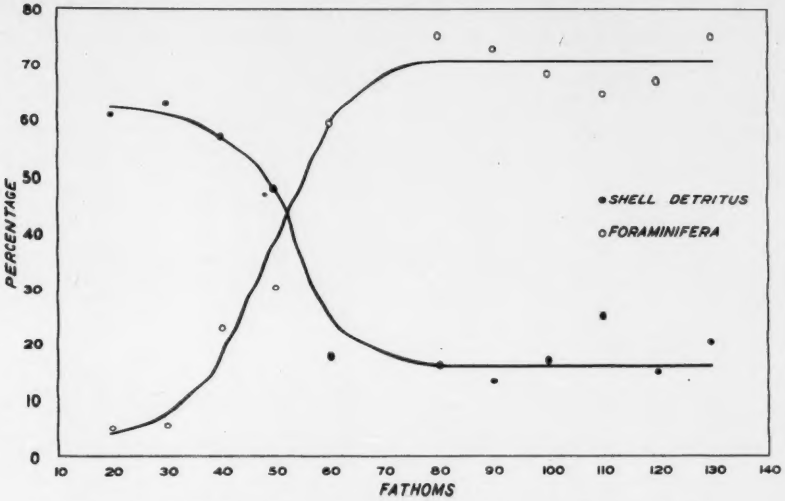


FIG. 3.—Relationship of the percentages of shell detritus and Foraminifera tests to the depth of the water.

The percentage of insoluble residue shows a general relationship to the topography. The top of the banks have low values, whereas, an increase in the percentage of insoluble material is noted downslope. A minimum value of 4.4 per cent is recorded from Tanner Bank at a depth of 42 fathoms, whereas a maximum value of 74.7 per cent is found in the Tanner Canyon area at a depth of 150 fathoms. The average percentage of insoluble material for the entire area is 37.5 per cent.

The low percentages of insoluble material in the shoal regions is attributed to the large volumes of calcium carbonate contributed by benthonic organisms of the euphotic zone, and to the lack of deposition of insoluble material. At depth, the supply of organic calcium carbonate is small and consists almost entirely of foraminiferal tests. Further, there is downslope transport of much of the fine insoluble material.

Mechanical analyses (table VI) of the insoluble material were made, and an average curve was prepared (fig. 2). A decrease in the average median diameters was noted, whereas the geometric sorting and phi skewness of the average sediment showed little change. The decrease in median value is caused by the rapid destruction by solution of very fine grained calcareous particles due to their large surface areas and relatively small mass. This results in a concentration of calcareous debris in the larger size grades. The digestion of the sediment in hydrochloric acid eliminates the control exercised by the coarse calcareous material, and causes a shift of medians to lower values.

Sediment Color

The colors of the recent sediments, when wet, were determined by comparison with a color chart prepared by Goldman and Merwin (1928). This chart is based on the Ridgway system of colors which yields both a color formula and the proper color nomenclature (Ridgway, 1912). The results of this study are listed in table I.

The two predominating colors noted

TABLE VI.—*Parameters of the insoluble residue of sediment*

Station no.	Insoluble Residue Per Cent	Median Diameter nn.	Sorting Coefficient	Phi Skewness	Grain Roundness
1	86.2	0.25	1.25	−0.035	A-SA
3	67.5	0.23	1.30	−0.035	A
4	46.1	0.74	1.36	−0.36	A
5	64.2	0.65	1.84	0.025	A-SR
6	35.2	0.26	1.25	−0.005	A-SA
7	24.8	0.13	1.38	0.02	A-SA
9	22.1	0.25	1.67	−0.16	SA
10	29.1	0.35	1.40	−0.045	A-SR
11	31.2	0.58	1.85	−0.10	A-SA
12	15.1	0.44	2.10	−0.46	A-SA
14	24.4	0.12	1.38	−0.06	A
16	10.7	0.44	1.78	0.05	A-SA
17	34.9	0.16	1.30	0	SA-SR
18	52.2	0.12	1.26	0	A-SA
19	89.7	0.14	1.16	0	A-SA
20	69.9	0.12	1.26	0.005	A-SA
21	60.8	0.21	1.39	0.015	A-SR
22	67.3	0.26	1.37	0.005	A-SA
23	35.2	0.43	1.80	−0.22	A
24	23.0	0.09	1.42	−0.08	A-SA
25	42.3	0.135	1.45	+0.055	A-SA
26	26.6	0.11	1.36	−0.105	A-SR
27	56.1	2.80	3.73	0.54	SA-SR
28	43.6	0.23	1.23	0	A-SA
29	59.5	0.12	1.28	0.005	SA
30	43.4	0.13	1.27	−0.04	SA-SR
31	74.7	0.18	1.25	0.005	SA-SR
32	69.6	0.21	1.18	−0.005	A-SR
33	56.5	0.23	1.40	−0.065	SA-SR
34	26.2	0.22	1.99	0.045	SA
35	7.1	0.19	2.02	−0.085	A-SA
36	4.4	0.32	1.34	0.065	A
37	29.9	0.27	1.16	−0.005	A-R
38	49.0	0.35	1.18	−0.015	SA-R
39	29.4	0.29	1.65	0.11	SA
40	55.4	0.21	2.62	0.12	SA-SR
41	7.0	0.27	2.36	−0.005	SA
42	9.5	0.16	1.84	−0.025	A
43	8.2	0.09	1.53	−0.31	SA
44	31.7	6.00	4.05	1.535	SA
45	26.5	0.35	2.00	0.015	R-SA
46	30.2	0.19	2.27	0.01	A-SR
48	11.5	0.08	1.22	−0.07	SA
51	56.7	0.37	7.00	−2.37	SA-SR
55	11.6	0.25	1.24	0.045	SA
60	4.4	0.107	1.61	0.13	A-SR
61	38.6	0.08	1.20	−0.035	SA
62	57.9	0.36	1.23	−0.035	SA
63	16.5	5.80	1.33	0.17	A
65	10.5	0.22	1.50	0.045	A-SA

are mineral gray and olive. There is a gradation from light mineral gray, at the top of the banks, to a deep olive at depth (pl. 7).

The gray results from a mixture of the white calcareous material and the dark detrital minerals; the higher the calcium carbonate content, the lighter the shade

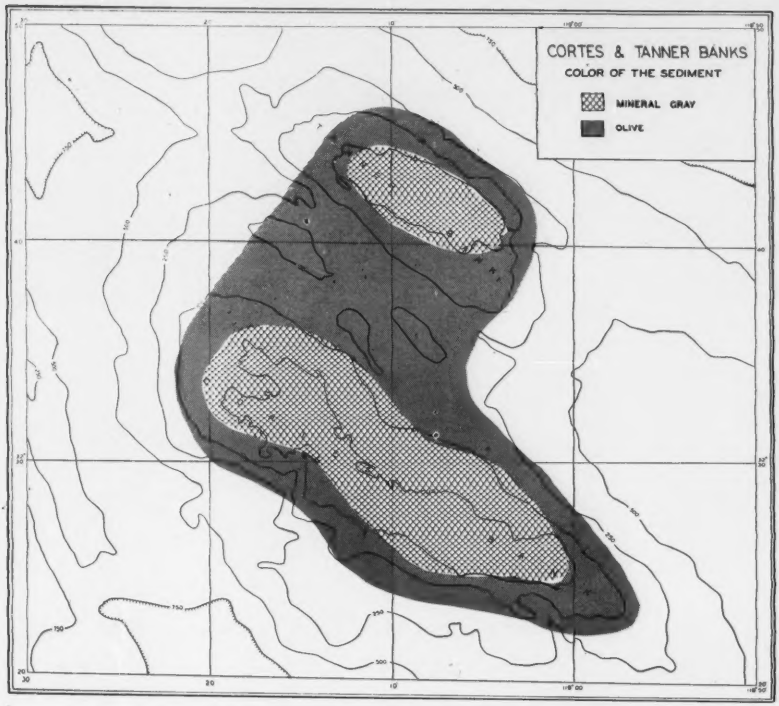


PLATE 7.—Chart illustrating color of the sediments.

of gray. Organic content was found to parallel closely the variations of the shade of the olive colored sediment; an increase in organic matter yielded a deepening of the olive color. The olive color may be further amplified by minute particles of glauconite which were not discernible, in abundance, in the size fraction used for petrographic studies.

Shape and Surface Texture

The majority of the detrital mineral grains are angular to subangular (table VI) with a fresh polished surface. A few grains are subrounded with a dull and slightly pitted surface. These are supposedly derived from the ancient sediments of the area, whereas the fresh angular material apparently originated from the destruction of the basalt porphyry.

The detrital mineral grains are residual and represent the products of an earlier erosional period associated with the terrace formation. Some submarine weathering may be in progress, but the nature and scope of such activity is little understood.

Mineralogy

The minerals of 14 sediment samples were identified, and the relative frequency of each mineral was determined. The samples selected for this study were scattered over the area and represent points on a rough grid system. By using a sampling technique of this nature,

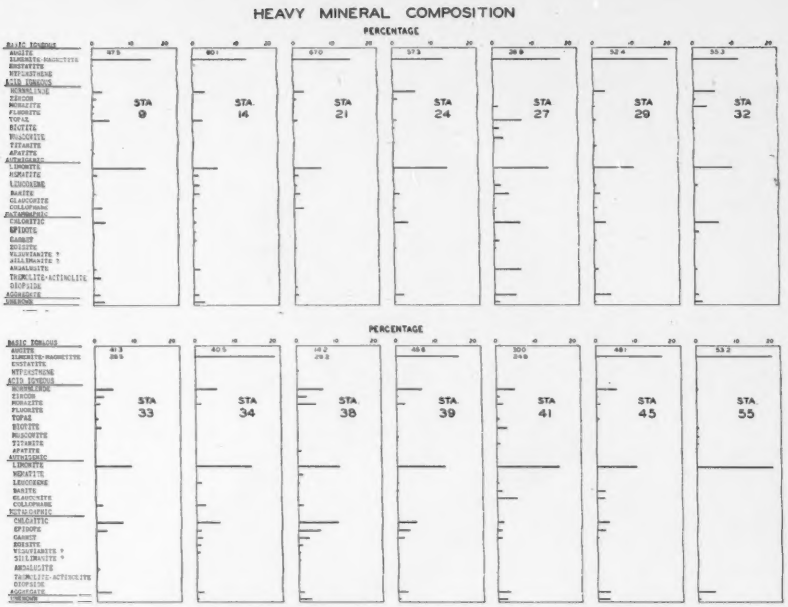


FIG. 4.—The heavy mineral composition of 14 sediment samples.

sufficient control was obtained to establish the mineralogical character of the sediment of Cortes and Tanner Banks.

Heavy liquid separations were made using acetylene tetrabromide, specific gravity 2.96, after which the heavy mineral fractions were mounted in aerochlor, refractive index 1.65. The light mineral fractions were studied in oils with a refractive index of 1.54. A petrographic microscope was used for the identification of the minerals, and abundance counts were made to determine the relative frequency of each mineral. A minimum of 200 grains were counted for each mount; the results of which are shown in figures 4 and 5.

The heavy minerals were grouped according to their probable source rock; and the average percentage, representative of each group, was computed. Figure 6 is a plot of these average values.

Basic igneous rocks are shown to be the source of 64.3 per cent of the heavy minerals of the bank area. The prime minerals of this basic suite are augite and ilmenite-magnetite, with augite predominating. The basalt porphyry, described earlier, is the probable source rock of these basic minerals.

Authigenic minerals, of which limonite is the most common, constituted an average of 16.0 per cent of the heavy minerals. Minerals of an acid igneous origin comprised 8.4 per cent; metamorphic origin was attributed to 7.5 per cent of the grains; whereas aggregate and unknown material make up the remaining 3.8 per cent. No minerals deemed characteristic of the Franciscan series were observed.

The light minerals of the sediment are predominantly plagioclase feldspar (fig. 5), derived from the destruction of the abun-

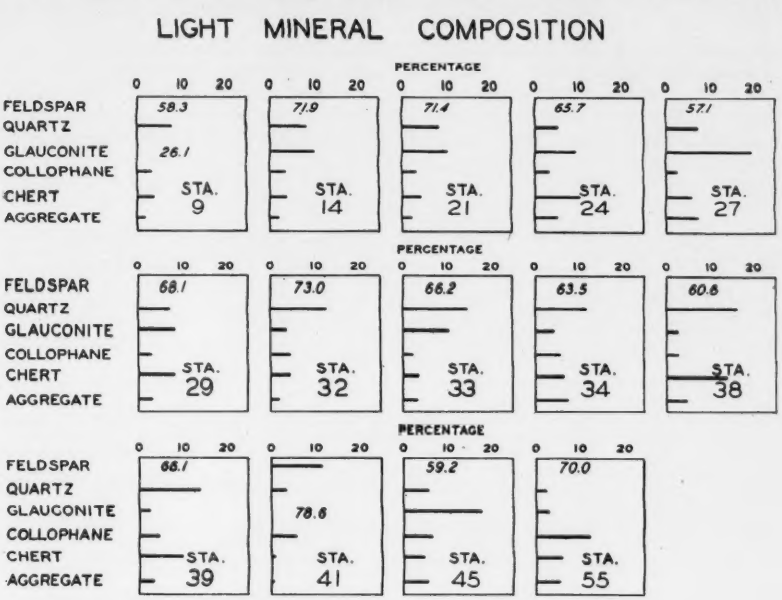


FIG. 5.—The light mineral composition of 14 sediment samples.

dant labradorite phenocrysts of the basalt porphyry. Sample number 41 showed an exceptionally high percentage of glauconite, 78.6 per cent, the reason for which was not apparent. Other light materials present were quartz, collophane, chert, and unidentified aggregate materials.

The character of the recent sediments is controlled by the topography, current activity, and the depth of water. The sediment from the top of the banks is coarse grained, contains abundant shell detritus; is light gray in color; and has a low organic carbon content. Down-

CONCLUSION

The Cortes and Tanner Banks area was subjected to a period of intense wave erosion at a time when sea level was at a relatively lower stand. An extensive terrace was cut in the sedimentary rocks at a depth of 40 to 60 fathoms, whereas topographic highs of basalt porphyry were left standing above the terrace level. The age of the sedimentary rock, and presumably the adjacent basaltic rock, is middle Miocene. No material of the Franciscan series was recovered from the area.

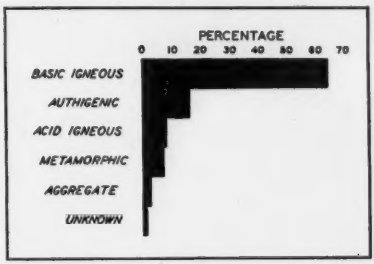


FIG. 6.—The average percentage of detrital heavy mineral grains derived from each petrologic source.

slope, the sediment becomes finer grained; is composed predominantly of foraminiferal tests; is olive in color; and reveals an increase in organic carbon content. The mineralogy of the detrital mineral grains is a direct reflection of the rock types exposed on the banks, and of the bank environment which favors the development of authigenic collophane and glauconite. Both these factors are in harmony in that they bear out the paucity of deposition in the area, and the residual nature of the detrital minerals.

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NOTES

THE TERMINOLOGY OF FINE-GRAINED DETRITAL VOLCANIC ROCKS

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Recent investigations in the volcanic rocks of the southeastern part of the Absaroka Range have shown that the widely-used terminology for most of the rock studied is inadequate and frequently misleading. Most of the rocks in this part of the Absaroka Range consist of volcanic debris of sand and silt sizes which has been transported by streams and deposited in a stream-channel and floodplain environment. Much of this volcanic detritus is the product of essentially contemporaneous eruptions, but some is the product of erosion of older, pre-existing volcanic rock. Such material has commonly been termed *tuff* by most geologists who have described the rocks of this area. The standard classification of pyroclastic rocks (Wentworth and Williams, 1932) offers no support for this usage, for *tuff* is a pyroclastic term, and *pyroclastic* has been defined as:

" . . . an adjective commonly applied to rocks produced by explosive or serial ejection of material from a volcanic vent. . . . It appears that the most careful usage would limit the term to detrital material which has been expelled aerially from a volcanic vent" (Wentworth and Williams, 1932, pp. 24 and 25).

Thus, *tuff* should be restricted to fine-grained fragmental volcanic rocks of known primary eruptive origin (or the definition of pyroclastic should be modified). Obviously, the deposits composed of detritus eroded from older volcanic rocks should not be called tuffs. Even the fluvial deposits which are the product of essentially contemporaneous eruptions are not tuffs, for their transportation and deposition has been controlled by hydraulics rather than serial factors. The application of the term *tuff* to these rocks is misleading.

In order to make more precise the discussion of the volcanic material found in the part of the Absaroka Range studied, a descriptive classification applicable to the fine-grained detrital volcanic rocks of non-pyroclastic and doubtful pyroclastic origin was found to be necessary. In this classification the adjective *volcanic* was prefixed to the terms used in the standard grade scale of Wentworth (1922, p. 381). An example would be *volcanic sandstone*. Wentworth and Williams give tacit consent to this system of nomenclature, for the term *volcanic conglomerate* is included (seemingly inconsistently) within their classification of pyroclastic rocks. Volcanic conglomerate is composed of debris transported and deposited by water and is not a true pyroclastic rock. If such a deposit is termed *volcanic conglomerate*, the stream-deposited volcanic material of finer grain size may logically be named in a similar fashion (*e.g.* volcanic sandstone).

There may, however, be some objection to consideration of the fine-grained fluvial deposits as *volcanic* rock, for to many geologists this term implies the coarser, more striking manifestations of volcanism such as lava flows, breccia, and conglomerate. However, in spite of this prejudice, the standard definition does support application of this term to the finer-grained derivatives. *Volcanic rock* is "any rock of volcanic origin" (Fay, 1920, p. 726), and *volcanic* has been defined by Fay (p. 726) as:

"—characteristic of, pertaining to, situated in or upon, formed in, or *derived from volcanoes*" [italics mine].

It has been found useful to further classify sedimentary volcanic rocks on the basis of per cent of volcanic material

present. For the purpose of recent study they were subdivided into three categories termed *lean volcanic* (less than 20 per cent of volcanic detritus), *medium volcanic* (20 to 80 per cent), and *rich volcanic* (80 to 100 per cent). Thus a sandstone containing about 10 per cent of volcanic detritus not clearly of pyroclastic origin was termed a *lean volcanic sandstone.*

Modification of the terminology of Wentworth and Williams for non-volcanic sedimentary rocks containing a subordinate admixture of fine-grained pyroclastic debris is also believed to be warranted. These authors (p. 50) use the term *sedimentary tuff* for this purpose. But this term is ambiguous, for it refers to a mode of origin rather than the composition of the rock. The use of the adjective *tuffaceous* for such rocks is believed to be more accurately descriptive and has been used in this way by others. Thus a sandstone containing less than 50 per cent of fine-grained pyroclastic debris would be termed a *tuffaceous sandstone.*

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REVIEW

Dana's Manual of Mineralogy, by C. S. Hurlbut, 16th ed. New York: John Wiley & Sons, Inc., 1952. Pp. 530 +viii; pls. XIII; figs. 471; $6.00.

Only two major changes have been made in the sixteenth edition of the "Manual." A new "Introduction" and a short section on "Crystal Chemistry" have been added.

The new "Introduction" presenting a short history of mineralogy, a good preview of the book, and the applications of mineralogy, is a definite improvement over that in the earlier edition. However, the following understatement appearing on page 11 in the Introduction may disarm many an unwary student. "It little matters what type of mineralogist one may eventually become; all must have a common core of knowledge, and the material presented in the following pages of this book can be considered the *minimum requirement*" (reviewer's italics). Most mineralogists and (sedimentary) petrologists probably will agree that the material in this book (or any other similar American text) is well below the minimum requirement even for the undergraduate geologist. On pages 14 and 15 of the Introduction, an application of mineralogy of interest to the budding sedimentary petrologist is given in a reference to C. S. Ross' study during World War II of the ballast sands from Japanese incendiary balloons.

The other major change is the insertion of a short section on crystal chemistry in Chapter 4, "Chemical Mineralogy." The treatment is extremely elementary and the applications are incomplete even for a manual. Certainly, at least references should have been given to some other elementary presentations, applications, and sources of essential background information on a subject so essential to the understanding of minerals (Ward, 1947; Stillwell, 1938; Henderson, 1951; Hauth, 1951; Bragg, 1937; Sisler, Vander Werf and Davidson, 1949; Pauling, 1947; Frederickson, 1951).

The part of Chapter 4 covering chemical tests is the same as in the preceding edition. Stain tests which have proven so useful to those studying carbonate rocks are still not given. The only changes in Chapter 2, "Crystallography" are: (1) simplification of some of the morphologic terminology, (2) substitution at last of the symmetry element *rotary inversion* for *rotary reflection*, (3) introduction of Hermann-Maugin symbolism.

The bulk of the book, consisting of descriptions of minerals, is essentially unchanged. The continued lack of adequate treatment of the clay minerals is of interest to sedimentary petrologists. Furthermore, although lip service is paid to the concept of solid solution, it still is not adequately emphasized or treated for many important groups of rock-forming minerals such as the carbonates, pyroxenes, amphiboles and micas. The merit of continuing to list separate descriptions and formulae for such "minerals" as phlogopite, tremolite, arfvedsonite, enstatite and diopside is questionable

Of the two or three minerals new to the book, only carnotite is likely to be of interest to sedimentary petrologists. Collophanite has at last been removed as a separately described "mineral." A four and one-half page description of the principal structural features of the silicates introduces that class of minerals.

A feature that seriously impairs the pedagogical value of the "Manual" is the absence of references. Only two references were noted in the entire book: both were in the "Introduction" and one of these was to the "Reader's Digest"! However, the improvements that have been accomplished in this edition prob-

ably put it on at least an equal footing with the other American texts in this field. Not the least of the appeal of the "Manual" is due to Hurlbut's lively and facile manner of presentation.

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